WATER AND AGRICULTURE IN CANADA: TOWARDS SUSTAINABLE MANAGEMENT OF WATER RESOURCES

The Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada

Council of Canadian Academies
Conseil des académies canadiennes

Science Advice in the Public Interest

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The Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada

THE COUNCIL OF CANADIAN ACADEMIES
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This report was prepared for the Government of Canada in response to a request from the Minister of Agriculture and Agri-Food. Any opinions, findings, or conclusions expressed in this publication are those of the authors, the Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada, and do not necessarily represent the views of their organizations of affiliation or employment.

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The following report reflects the efforts and contributions of 15 experts drawn from diverse fields of expertise from Canada and abroad. I am deeply grateful for my colleagues on the Panel who contributed so much of their time and effort to ensure the depth and quality of this report. The result embodies the Panel's collective insights and judgment, and an undertaking of this magnitude would have been impossible without their wisdom and support.

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Howard Wheater, Chair

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Report Review

This report was reviewed in draft form by the individuals listed below — a group of reviewers selected by the Council of Canadian Academies for their diverse perspectives, areas of expertise, and broad representation of academic, policy, and non-governmental organizations.

The reviewers assessed the objectivity and quality of the report. Their submissions — which will remain confidential — were considered in full by the Panel, and most of their suggestions were incorporated into the report. They were not asked to endorse the conclusions nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the Expert Panel on the Sustainable Management of Water in the Agricultural Landscapes of Canada and the Council of Canadian Academies.

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The role of the report review monitor is to ensure that the panel gives full and fair consideration to the submissions of the report reviewers. The Board of Governors of the Council authorizes public release of an expert panel report only after the report review monitor confirms that the Council's report review requirements have been satisfied. The Council thanks Dr. Krewski for his diligent contribution as review monitor.

EDowdeswell

Elizabeth Dowdeswell, O.C., President & CEO
Council of Canadian Academies

Executive Summary

The agricultural sector is an important contributor to Canada's prosperity and well-being. Primary agriculture plays a vital role in the food sector which is linked to close to $100 billion per year in economic activity and approximately 1 in 7.5 jobs. It is a key source of food security and a support for rural communities. And for many Canadians, it is not just a source of income, but a way of life.

There are substantial opportunities for Canadian agriculture in the coming decades. Population growth and other factors are projected to more than double global demand for food by 2050, while rising world incomes shift global patterns of food consumption towards higher value (but more water-intensive) forms of agricultural production (e.g., meat and dairy products) and increase demands for non-food agricultural products such as biofuels and natural fibres.

At the same time, growing competition for water, land, and other resources, as well as the uncertain impact of climate change and climate variability, will place increased stresses on agricultural production throughout the world. Within Canada, significant risks and uncertainties include agriculture's impact on water quantity and water quality; the agricultural sector's access to water, land, and other resources; and how the sector can meet the challenges posed by climate change and other developments. These risks and uncertainties must be addressed expeditiously for Canada to maintain a robust agricultural sector that can seize opportunities and contribute to meeting the world's food needs.

To help prepare for these opportunities and challenges the Minister of Agriculture and Agri-Food (the Sponsor) asked the Council of Canadian Academies (the Council) to assemble a panel of experts to address the following question:

> *What additional science is needed to better guide sustainable management of water to meet the needs of agriculture?*

In response to this question, the Council assembled a multidisciplinary panel of Canadian and international experts with backgrounds in hydrology, agriculture, climate, engineering, economics, water management and governance, and other fields. The Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada (the Panel) gathered and analyzed evidence pertaining to areas such as Canada's water resources, water futures for agriculture and other industries, agriculture and the environment, Beneficial Management Practices (BMPs) from Canada and other countries, trends in technology and innovation, public policy frameworks and economic instruments, and communication and stakeholder engagement aspects of land and water management. Information from this review was combined with the Panel's expertise, experience, and judgment.

THE FINDINGS

After a review of the existing evidence, the Panel identified five key areas in which additional science and required action can contribute to better sustainable management of water in agriculture. The following overview summarizes these under five headings, corresponding to each of the main chapters in the report.

1. *Achieve a better understanding of risks and uncertainties in areas such as market conditions, competition for land and water resources, and climate change to inform management decisions, leading to more effective management practices and outcomes (discussed in Chapter 2).*

Identifying what additional scientific knowledge is needed for sustainable management of water in Canadian agriculture requires an understanding of the main global drivers affecting the future of the agricultural sector, as well as the economic, environmental, and social contexts in which Canada's agricultural sector operates. For the purpose of this report, the Panel examined the scientific evidence that refers to future trends and possibilities up to 2050. The Panel observed that during this period, changing market conditions are likely to result in new export opportunities, calling for more water-intensive forms of agricultural production. This would be happening at a time when urban and industrial development, climate change, and other factors will place greater pressures on land, water, and other resources in Canada and around the world. Moreover, given the resulting intensification in the competition for resources, social pressures may also require the agricultural sector to demonstrate more effectively its contributions to economic growth, food security, and environmental protection, while regulatory and non-regulatory risks may require changes to production methods and locations. Additional research in these and other areas of opportunities, risks, and uncertainties can help agricultural producers, government policy-makers, and other stakeholders make more informed decisions in production planning, infrastructure investments, and agricultural policies.

The Panel believes that priority areas include research on changing market conditions, policies, and social perceptions that may present new risks and opportunities for agriculture; implications of heightened competition for land, water, and other resources; and impacts of climate change and increased climate variability in agricultural regions across Canada. The Panel noted that climate change is likely to pose increasing challenges for agriculture world-wide. Some of the world's major agricultural regions can expect substantially less precipitation. Across Canada, changing climate will affect both growing conditions for dryland agriculture, and the surface water and groundwater resources that support irrigation and livestock operations. Globally, increasing frequency of extreme weather events, including floods and droughts can be expected; recent events in North America and world-wide have shown the potential implications for global food production. In Canada, the Prairies have a history of flood and drought. The Panel was concerned to note that new research suggests an increasing risk of extreme Prairie drought under climate change scenarios. The Panel observed that given the high levels of uncertainty concerning future conditions, new approaches will be needed to support development of policy, governance, and management of water for agriculture. In particular, research is needed into the potential for adaptive management to provide robust strategies that can assist in accommodating uncertainty in water futures, and the role of foresight studies in informing those strategies.

2. *Improve monitoring information targeted to specific areas of concern using a risk-based approach, as well as enhance scientific capacity for the interpretation of these data to foster a better understanding of Canada's water resource base and ongoing changes in hydrology, ecology, and climate, and to facilitate adaptive management (discussed in Chapter 3).*

Access to a reliable supply of sufficient fresh water resources is a fundamental requirement for agriculture. Most agricultural production depends on natural precipitation (rain or snow), sometimes called "green water." Concerns about water for precipitation-fed agriculture focus on (a) climate suitability for crop production (i.e., the reliability of adequate precipitation from year to year, the extremes of too much or too little water, and climate change); (b) managing the land to optimize the water environment for crops (e.g., through drainage or tillage practices); and (c) the impacts of agricultural activities on the quantity and quality of water in surface water and groundwater systems.

Irrigation and other agricultural uses of water (e.g., for intensive livestock production, or food processing) rely on surface water sources (rivers or lakes) or groundwater aquifers. This is sometimes called "blue water" and its use often competes with other demands for water (e.g., drinking water, other urban water use, industry, hydropower, or to maintain healthy ecosystems). Irrigation is essential for agriculture in areas where natural precipitation is low and/or variable, and it can also generate increased productivity, diversity (high-value crops), and product quality. Irrigation is also, however, the world's largest consumer of blue water (70 to 80 per cent of global water consumption). Concerns for blue water use include the quantity and quality of the available water, as well as the impacts of agricultural activities on the quality of surface water and groundwater resources.

A serious threat to the health of the agricultural sector is water stress, whether related to the quantity or the quality of water used by agriculture or the quantity or quality of water flowing from agricultural lands. Causes of water stress depend on local conditions. In parts of the Prairies, for example, irrigation is a dominant consumer of blue water in areas where water resources are fully allocated, while the region's green water supply has been affected by both major floods (e.g., 2011) and droughts (e.g., 2001–2002). In regions of British Columbia, agricultural uses of water face significant competition from other users and the environment. For instance, the Okanagan Valley, a region where agricultural activity depends on irrigation, has seen significant population growth in recent years and is already nearing or exceeding the available water supply. Contamination of surface water and groundwater bodies due to agricultural runoff is a major concern in most agricultural regions across the country.

With stress on water resources projected to increase in the future, agriculture and other sectors need to work toward developing more efficient and sustainable methods for managing water use and consumption. Improved water monitoring is needed for contributing to this effort by providing decision-makers and stakeholders with the information they need to manage water more effectively. However, Canada does not currently possess the data and jurisdictional coordination necessary to fully understand either the quantity or quality of fresh water resources across the country, especially in less populous areas, or to adequately define the water currently used by agriculture and needed for future agricultural purposes.

The Panel believes that improvements in water quantity and quality monitoring and modelling would provide for better risk management in agriculture. Such information is critical to informing the development of adaptive management strategies that will be essential in helping agricultural producers, policy-makers, and other stakeholders to accommodate heightened uncertainties relating to market conditions, climate, and other risks. The Panel also suggests that the development of integrated water and climate monitoring and forecasting capabilities could make substantial contributions to Canada's ability to sustainably manage its water resources for agriculture, providing much needed input for mitigating risks, capitalizing on opportunities, and informing policy and management decisions.

3. *Achieve a better understanding of the complex interactions between land management and water resources, including assessment of the economic and environmental efficacy of BMPs and the potential for conservation agriculture and ecosystems services approaches to the management of natural resources (including land and water) (discussed in Chapter 4).*

Agriculture can affect the physical environment in complex ways through irrigation, tillage, drainage, and other land and water management practices. Certain impacts on water quantity, water quality, and habitats are controversial, but they remain poorly understood and quantified. One such example is the loss of wetlands through agricultural drainage, which is an issue that can be a source of conflict between different parts of a community.

One of the major water quality issues arises due to high nutrient loads, particularly nitrogen and phosphorus. Issues of concern in Canada include high phosphorus concentrations in the Prairies. Associated effects on rivers and lakes include algal blooms, with implications for ecosystems, drinking water, and recreation. Other impacts on ecosystem health, recreation, and drinking water quality include high nitrate concentrations in areas such as Prince Edward Island, with concentrations in groundwater and some surface water sources exceeding drinking water standards. Pressures like these are seen world-wide. In Europe, one recent study estimated that reactive nitrogen effects from agriculture resulted in between €20 and €150 billion of environmental damage per year, compared to the benefit of nitrogen fertilizer to farmers, which was valued at between €10 and €100 billion per year. Other issues include impacts on water quality from pathogens, pesticides, and veterinary medicines.

As efforts to increase agricultural production intensify, issues pertaining to agriculture's impact on water and the environment will become more pressing, particularly as additional pressures are also being exerted by population growth, urban expansion, and industrial development.

Although agriculture is associated with some of the effects on water quality and the environment stemming from global intensification, there are many opportunities to manage agriculture's relationship to the water environment in ways that increase water use efficiency and enhance environmental protection. BMPs, technological innovations, governance strategies, and policy tools are some of the ways in which this can be accomplished. Given the various concerns for agriculture's adverse effects on the water environment, and the particular concerns for nutrients, a critical policy question will be determining the potential for various mitigation options, such as BMPs, technologies, governance strategies, and policy tools, to reduce these effects.

BMPs also provide the context for two related concepts that offer the potential for important benefits connected with a more diverse agricultural sector: conservation agriculture, which aims to create resilient, productive landscapes in the face of uncertain futures; and an ecosystem services approach, which recognizes the value of non-marketable services, such as flood control, water quality, and ecological diversity. These broader perspectives on the role of agriculture in providing a wider range of ecosystem goods and services to society could provide significant benefits and opportunities for the agricultural industry.

Important research priorities therefore concern quantification of the effects of agricultural land management practices on water quantity and quality and on ecosystem health, and the potential of BMPs to mitigate those effects. Particular issues include:

- the local and regional impacts of changing cropping and tillage practices on runoff processes and water quality;
- the role of agricultural drainage and loss of wetlands on flood risk, drought resilience, water quality, and habitat at local and regional scales; and
- the potential effects of BMPs on nutrient loads to surface water and groundwater systems.

Addressing this latter issue will require targeted research on BMP performance that quantifies local and regional scale effectiveness, identifying the best means for encouraging uptake of sustainable practices and technologies, and assessing options for the sharing of costs and benefits among different stakeholders, including the public. The Panel maintains that the development of an ecosystems services perspective on the role of agriculture requires significantly improved data on the relationship between agriculture, habitat, and biodiversity than are currently available.

4. *Improve knowledge of promising farm-scale technologies and research priorities, contributing to better water use efficiency, reduced environmental impacts, and sound investment decisions by governments, industry, and agricultural producers (discussed in Chapter 5).*

Technological developments have had dramatic impacts on the overall productivity of agricultural systems and experts are optimistic about the future improvements in productivity that can be achieved. Within Canada, there is a range of technological options relating to irrigation, precision and smart agriculture, pesticide and fertilizer formulation, low-cost water treatment, and many other areas that can contribute to maximizing opportunities and managing risks by improving water use efficiency, mitigating environmental impacts, and enhancing the productivity and resiliency of agriculture.

The Panel believes that additional research is needed to better understand the priority options that can provide the greatest contributions to improving water use efficiency, mitigating environment impacts, and enhancing the productivity and resiliency of agriculture. Targeted research is also needed to better understand the options and priorities most appropriate to each agricultural context. In addition, demonstration projects and agricultural extension are necessary to increase the uptake and successful deployment of technological developments and other research.

5. *Build a foundation for sustainability by adopting appropriate governance structures, valuation techniques, economic incentives, and knowledge transfer strategies to facilitate better management decisions, improve uptake of sustainable practices, and enable the agricultural community to build strong working relationships with other sectors and stakeholders to resolve cross-sectoral issues (discussed in Chapter 6).*

Based on its research and deliberations, the Panel concludes that effective governance is an essential prerequisite to sustainable water management in agriculture. Water governance in Canada is highly fragmented, with multiple levels of government holding or sharing responsibility. Contemporary water governance processes are diverse and include traditional regulatory approaches, collaborative processes, and market-based processes — as well as combinations of all of these. The roles of non-government actors, indigenous peoples, civil society groups, and businesses are increasing and changing relative to previous decades. Consequently, a host of new challenges exist relating to the effectiveness, capacity, legitimacy, and accountability of management decisions. Understanding how best to address these challenges is uneven.

Differences in legal regimes, institutional settings, and socio-economic contexts across the country mean that there is no single framework that will be effective in all jurisdictions. Therefore, the Panel focused on principles and promising practices that have been shown to be effective in supporting sustainable management of water resources. These include:

- Ensuring governance operates at the appropriate scale, which can help to facilitate coordination of management efforts across relevant jurisdictions and stakeholders.
- Integrating land-use planning with water management decisions, which can assist in incorporating the needs of multiple users, while ensuring sustainable water management in the long run.
- Incorporating knowledge into the decision-making process (including scientific, traditional, and local knowledge), which can lead to more robust solutions that account for the complex and interconnected nature of current water management and governance challenges. Transdisciplinary research, where researchers and partners from the farm community, industry, and government jointly define problems and research programs, is an important way to facilitate knowledge co-production.

Agricultural policy strongly influences stakeholder decisions that affect water use in agriculture, often striving to ensure the sector is economically competitive, while also addressing relevant environmental and social concerns. Experiences from across Canada and around the world demonstrate that economic instruments — when designed properly and implemented appropriately — can support the goal of sustainable water management. The Panel considered the potential for economic valuation techniques, economic incentives, pricing, and water markets to contribute to sustainable management of water for agriculture. Investigation of how these tools can be used effectively in the Canadian context is needed, as are mechanisms to measure their success.

Water governance decisions also need to incorporate the views and opinions of stakeholders. Stakeholder engagement should both disseminate information to the public and encourage a sense of responsibility over the sustainable management of water. Consequently, the Panel maintains that research into knowledge transfer strategies, as they relate to agriculture and water use, can contribute to improving communication between decision-makers and relevant stakeholder groups (including the public). This will be critical for addressing the cross-sectoral issues that affect sustainable management of water for agriculture.

MOVING FORWARD

The mix of opportunities, risks, and uncertainties for agriculture will vary by subsector and region. Decision-makers, therefore, need to adapt and apply solutions that are tailored to their particular circumstances. Doing so will require additional research, time, and investment. It will also require a concerted action by all stakeholders in their respective areas of responsibility, combined with a collaborative effort to coordinate activities and integrate knowledge from across jurisdictions. To prepare for the future, it is essential that such efforts begin now to ensure that the Canadian agriculture sector can remain resilient and continue to be a leader in productivity and innovation, as well as an important contributor to Canada's economic growth, food security, and the well-being of local communities.

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Introduction

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1 Introduction

The future holds tremendous opportunities for the agricultural sector. Growth in the world's population is set to more than double the demand for food production by 2050 (de Fraiture *et al.*, 2007; FAO, 2009). Innovation is creating new markets for biofuels, bioindustrial products, and other non-food agricultural products (AAFC, 2011a; Boehlje & Bröring, 2011; Knickel *et al.*, 2009). Furthermore, rising incomes are poised to expand demand for agricultural goods of all types (de Fraiture *et al.*, 2007; UNESCO, 2009).

Canada can benefit from these global opportunities. With annual sales of $35.2 billion, Canada is the fourth largest exporter of agriculture and agri-food products (including food and other non-food agricultural products) after the EU, the U.S., and Brazil.[1] Primary agriculture alone produced $51.1 billion in gross farm receipts in 2011 (Statistics Canada, 2012). Moreover, the wider "food sector" (including sub-sectors such as food and beverage processing, food service, and food retail and wholesale), in which primary agriculture plays an important role, has been linked to as many as 1 in 7.5 jobs in Canada and close to $100 billion in economic activity (AAFC, 2011c; The Conference Board of Canada, 2011).

To take advantage of these opportunities, the Canadian agriculture sector will need to carefully manage its relationship with the environment and with water in particular. Water is essential for agriculture as precipitation or irrigation for crops, or water for livestock. At the same time, agricultural activities affect water quality and quantity. Agriculture is both a major consumer of water (comprising 66 per cent of Canadian water consumption) (NRTEE, 2010a) and an important dimension of the rural landscape (with the potential to enhance or degrade that environment) (Eilers *et al.*, 2010; Molden *et al.*, 2007a). It is popularly believed that Canada has an abundance of water (Sprague, 2007). In reality, most of this water is located in regions where agriculture does not take place (Kreutzwiser & de Loë, 2010). Many important agricultural regions in Canada, including parts of the Prairies and portions of British Columbia, are already water-stressed, and concerns about water quality exist throughout most of Canada's agricultural lands (AAFC, 2007a; NRTEE, 2010a; Stewart *et al.*, 2011).

Water and the rural environment are also necessary for many other economic sectors and human activities. Urban centres, industrial users, outdoor recreation, and wildlife all depend on clean water and usable land areas. Water is also essential for energy production (e.g., for hydropower generation and for cooling thermal power stations).

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[1] Calculations based on AAFC, 2011c.

To prosper in the coming years, agricultural producers, rural and urban communities, industrial water users, provincial/territorial and federal government departments, and stakeholders must work together to ensure that water is managed in a sustainable way. In particular, agriculture's reliance and impact on water (both its quality and quantity) is a critical issue to ensure the sustainability of the agricultural sector, rural communities, and the Canadian economy.

At the same time, climate change, rapidly changing market conditions, and shifting public perceptions create considerable uncertainty for the agricultural sector (AAFC, 2011a; Motha & Baier, 2005; Rude & Meilke, 2006; Sarris, 2009). The impacts of these changes on production levels, input costs, and profitability will be positive in some areas and negative in others.[2] The agricultural sector and other stakeholders therefore need a clearer idea of the risks that will be created by these changes, and how these risks can be managed.[3]

How might such challenges be addressed? The international water community has recognized that our well-being depends on the extent to which water is used and managed *sustainably* (UNESCO, 2009). This will require the Canadian agriculture sector to become a leader in sustainable water management, which Environment Canada defines as "the use of fresh water in an efficient and equitable manner consistent with the social, economic, and environmental needs of present and future generations" (Environment Canada, 1987). Achieving this goal will call for knowledge, innovation, and the integration of ideas, practices, and know-how across several areas of social, health, natural, and engineering science.

Canada must first clearly define "the needs of present and future generations," as well as the right instruments for determining these needs and bringing about the social action required to meet them. Understanding the interconnections among the agricultural sector, the environment, the economy, and society is also crucial, so as to determine the real trade-offs among the decisions to be made. So too is knowing how agriculture can enhance efficiencies through harnessing the latest technologies and Beneficial Management Practices (BMPs) in ways that distribute the costs fairly across the full range of beneficiaries. Effective governance and management are required because many of the challenges faced by the agricultural sector relate to shortcomings in the way decisions are being made about water. Jurisdictional fragmentation, weak institutions, and a lack of coordination are some of the governance challenges that must be addressed in order to achieve sustainable water management. These areas

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[2] On potential impacts of climate change, for instance, see NRCan, 2004; NRTEE, 2010b. With respect to markets and public perceptions, see AAFC, 2011a; Sarris, 2009.

[3] For an example of the range of scenarios, see Flörke & Eisner, 2011.

of knowledge should provide a focus for the efforts needed to help achieve the goal of an agricultural sector that is competitive, innovative, and sustainable (AAFC, 2011a, 2011b). It is also urgent that Canada acts quickly to guide the next round of investments in policies, programs, and infrastructure towards a sustainable framework for water management in agriculture.

1.1 CHARGE TO THE PANEL

To help Canada in preparing for these opportunities and challenges, the Minister of Agriculture and Agri-Food (the Sponsor) asked the Council of Canadian Academies (the Council) to assemble a panel of experts, the Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada (the Panel), to address the following question:

> *What additional science is needed to better guide sustainable management of water to meet the needs of agriculture?*

Further to the main question, the following sub-questions were posed:

- *What is the state of water resources in Canada for agricultural use in Canada and how is this affected by major competing rural demands, such as consumption by local industry and recreational use?*
- *What more do we need to know regarding the water cycle and utilization of water in order to understand the adequacy and value of water supply in rural areas?*
- *What additional knowledge is required to understand sustainable practices and possible adverse effects related to use of water in rural areas?*
- *What additional knowledge and monitoring practices are required in order to make progress on gathering and using bio-physical information to optimize the use of water?*
- *What additional socio-economic and environmental information and analysis needs to be considered for the sustainable management of water in rural areas?*

1.2 COUNCIL PROCESS

To address the questions posed by the Sponsor, the Council assembled a multidisciplinary Panel of Canadian and international experts in hydrology, agriculture, climate, engineering, economics, water management and governance, and other fields. During the Panel's initial deliberations it gathered and analyzed evidence related to Canada's water resources, water futures for agriculture and other industries, agriculture and the environment, BMPs from Canada and other countries, trends in technology and innovation, public policy frameworks, and principles that have been shown to be effective possibilities for incorporating stakeholder values into water management decisions. Information from this review was combined with the Panel's expertise, experience, and judgment. The preliminary report produced as a result of this work then went through a rigorous peer review by Canadian and international experts drawn from a diverse range of fields relevant to this assessment. The final report incorporates the feedback of the reviewers.

1.3 SCOPE OF THE ASSESSMENT AND KEY DEFINITIONS

The scope of this evidence-based assessment was determined by the questions from the Sponsor and by the definitions of a number of key concepts. This assessment examines the science needed to sustainably manage water for agriculture in the future. Here, *science* is defined broadly to include the natural, social, and health sciences as well as engineering and the humanities, all of which help us understand how to best manage water resources to meet the needs of agriculture and of other users. As stated previously, sustainable management of water in agriculture entails meeting "the social, economic, and environmental needs of present and future generations" (Environment Canada, 1987). The Council's earlier assessment on *The Sustainable Management of Groundwater in Canada* (CCA, 2009) further describes sustainable management as encompassing five elements: (1) protection of water supplies from depletion; (2) protection of water supplies from contamination; (3) protection of ecosystem viability; (4) achievement of economic and social well-being; and (5) application of good governance. The Panel incorporated each of these considerations into its definition of sustainability in this report and added a sixth element: integration of the needs of future generations (see Figure 1.1).

For the purposes of this assessment, the Panel defined the *agricultural sector* as primary production (of crops and livestock). It does not include further secondary processing of food products (such as bakeries or canneries) or the larger agriculture and agri-food value chain — including input and service suppliers (e.g., pesticide companies, banks, and insurance companies), food retail and wholesale trade, and food service industries. The Panel believes that this definition best reflects the Sponsor's focus on water use in the primary agricultural sector.[4] That said, the Panel notes that primary agriculture is an important contributor to the wider agriculture and agri-food value chain and the economy. As agreed with the Sponsor at the outset of the assessment, the Panel makes no distinction between urban, agricultural, and rural water demands throughout the report as they are all part of the same hydrological system.

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[4] For definitions of *agriculture* and other sub-sectors, see AAFC, 2011c.

Adapted from CCA, 2009

Figure 1.1

Elements of Sustainable Management of Water for the Needs of Agriculture

This figure presents the five elements from the assessment *The Sustainable Management of Groundwater in Canada*. This Panel included a sixth element to complete this figure: integration of the needs of future generations.

There is also an important distinction between *water use* and *water consumption*. *Water use* includes both in-stream and withdrawal (or off-stream) uses. In-stream uses occur when water is used in its natural setting, as with boating, water-based recreation, and hydroelectric power (Environment Canada, 2011a; Kohli *et al.*, 2010; Turner *et al.*, 2004). Withdrawal uses occur when water is taken out of its natural setting (e.g., a river or groundwater source) and used for purposes such as industrial activities or irrigation for agriculture (Environment Canada, 2011a; Kohli *et al.*, 2010; Turner *et al.*, 2004). Withdrawal uses may "consume" some or all of the water taken from the source, meaning that the water taken is not necessarily returned to the source.

Examples of *water consumption* include water that evaporates during industrial use, water that plants or livestock retain, water incorporated into products such as food and beverages, and water withdrawn for irrigation and lost to the atmosphere by evapotranspiration (Environment Canada, 2011f; USGS, 2008). The portion of agricultural water withdrawals incorporated into products marketed outside of Canada is part of the global flow of "virtual water" (Chapagain & Hoekstra, 2008).

In any given area, various human water uses may compete with each other for the same water resource and also with ecosystem needs. Consumptive use is one example, but there are others. Flow rates or water levels that are altered by a dam — a form of in-stream use — can affect the viability of local ecosystems and the quality and availability of water for other uses (Environment Canada, 2011a; Young, 1996). Water returned to the environment from withdrawal uses may also be degraded, as in the case of effluents containing human, animal, or industrial waste (Environment Canada, 2010c). The Panel considers all these uses when analyzing sustainable water management in agricultural landscapes. These human uses, together with ecosystem needs, define the term *competing uses* in this report.

For the purpose of this report, the Panel has examined the future trends and possibilities relevant to sustainable management of water for agriculture up to 2050 (e.g., increased demands for food and other agricultural products; competition for water resources from non-agricultural uses such as industry, municipalities, and hydroelectricity; and the potential impact of climate change).[5] Beyond this time frame, the levels of uncertainty become so large as to make most analyses overly speculative given potential changes in demands, climate conditions, technologies, and other factors. Indeed, the Panel acknowledges there are significant uncertainties in projections in commodity markets and climate variability even up to 2050; however, it believes that policy- and decision-making can benefit from the foresight that scientific evidence provides on these potential future scenarios.

Future allocations of water will be determined not only by economic imperatives and market conditions, but also by social values and ethical considerations. Numerous economic tools (e.g., monetary incentives, market trading systems) and policy instruments (e.g., regulatory regimes, governance structures) can be used to achieve objectives such as sustainable use of water and increased economic competitiveness and innovation. Society will need to evaluate and prioritize those objectives it most wants to achieve. Governments and stakeholders will also need to communicate effectively and build consensus on which objectives provide the best possible economic, environmental, and social outcomes for the widest group of stakeholders, including the Canadian public. This evaluative and decision-making process will require three main inputs:

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[5] Regarding these trends and possibilities, see IPCC, 2007; UNESCO, 2009, 2012 and the discussion in Chapter 2 of this report.

1. The scientific knowledge and expertise to understand the objective facts that relate to current and future water quality and availability, technological opportunities and trends, and economic opportunities and trends.
2. The governance strategies and policy tools to make effective water management decisions and to influence behaviours.
3. The effective engagement of stakeholders both within the primary agricultural sector and across other groups of water users (e.g., industries, communities, watershed authorities, provincial and federal government departments, and the public) to determine what management practices, technologies, policy tools, and governance structures achieve the best possible outcomes for stakeholders and the public.

For all of these reasons, the Panel has adopted a very broad approach to the economic, technological, environmental, and social knowledge stated in the sub-questions and required for sustainable management of water in agriculture. The Panel has also sought to highlight promising practices for integrating these areas of knowledge across the report.

1.4 ORGANIZATION OF THE REPORT

This report is organized according to the main issues that the Panel identified as needing to be addressed in order to answer the questions posed by the Sponsor. Chapter 2 (The Global and Canadian Contexts of Water for Agriculture) begins by outlining the main global drivers affecting the future of the agricultural sector and discusses the implications of these drivers within the Canadian context. It illustrates that while the next several decades will offer tremendous opportunities for Canadian agriculture, there are also significant risks and uncertainties that need to be carefully managed to ensure the sustainability of the sector.

Chapter 3 (Knowledge Inputs for Management Decisions) continues by examining what we know and what we need to know in order to manage water resources for agriculture in a sustainable way. It shows that several agricultural regions across the country are already water stressed, and identifies a range of potential threats to water availability and quality that need to be better understood to promote the sustainable management of water for agriculture. Limitations in current monitoring, evaluation, and modelling are identified, which if addressed would provide the essential support for improved water quality and quantity management. Both land and water management face major uncertainties associated with changing climate; new approaches will be needed for adaptive management.

Chapter 4 (Land and Water Management) explores the interconnections between land and water management. It explains how land use patterns, drainage practices, irrigation, and other land and water management decisions affect the demand for water, agricultural productivity, water quality, and ecological systems, and thereby influence various economic, environmental, and social outcomes. It also analyzes how BMPs can enhance such outcomes for a range of stakeholders, though noting that, like any management decisions, such practices need to be systematically and continually assessed to determine their cumulative impact on the water environment. The chapter concludes with consideration of the need for a shift towards a conservation agriculture approach in which diversity is enhanced to provide more robust and resilient production systems and an ecosystem services perspective on agriculture. In this perspective, agriculture and farmers are considered not simply as places and people that produce food products but rather as places and people that sustain and maintain landscapes that provide a great many of the ecosystem services that society desires.

Chapter 5 (Promising Farm-Scale Technologies) focuses on promising technological opportunities that can contribute to improving water use efficiency and mitigating the environmental impacts of agricultural production. Although the diversity and complexity of the Canadian agriculture sector means that only certain technologies will be appropriate given sub-sectors and local conditions, the objective is to offer a selection of general possibilities that can be adapted as deemed appropriate by producers, policy-makers, and stakeholders.

Chapter 6 (Building the Foundation for Sustainable Management of Water in Agriculture) examines the challenge of integrating economic values, environmental needs, and societal expectations in water management decisions. It outlines how governance structures, valuation techniques, economic incentives, and knowledge transfer strategies that consider these values can help to achieve the goal of sustainable water use in agriculture. In doing so, it notes that achieving any particular set of objectives requires that the goals are clearly defined at the outset and that relevant stakeholders have been engaged.

Finally, Chapter 7 (Conclusion) completes the analysis by providing an overview of the key risks, opportunities, research needs, and required actions, discussed throughout the report and summarizes the Panel's answers to the main question and sub-questions posed by the Sponsor.

2

The Global and Canadian Contexts of Water for Agriculture

- The Global Context: Opportunities and Challenges
- The Canadian Context: Water, Climate, and Economic and Social Dimensions
- Responding to Opportunities and Challenges: Adaptive Management

2 The Global and Canadian Contexts of Water for Agriculture

Overview

Increased demand for food and other agricultural products will present numerous opportunities for the agricultural sector over the next several decades. To maximize these global opportunities, risks and uncertainties — related to, for example, changing market conditions, heightened competition for land and water resources, and climate change — will need to be carefully managed to ensure the sustainability of the Canadian agriculture sector. Conventional prediction-based approaches to policy have important limitations in managing uncertain futures. The Panel believes that the principles of adaptive management offer a useful conceptual framework for better addressing these uncertainties and risks.

Identifying what additional scientific knowledge is needed for sustainable management of water in Canadian agriculture begins with understanding the main global drivers affecting the future of the agricultural sector, as well as the economic, environmental, and social contexts in which Canada's agriculture sector operates (see Figure 2.1). Section 2.1 of this Chapter builds on this conceptual framework by exploring the potential implications of the most significant global drivers, while Section 2.2 provides an overview of the Canadian context. Section 2.3 then concludes by identifying the main areas in which the Panel believes there is a need for additional science to take advantage of global opportunities while better guiding sustainable management of water for agriculture.

2.1 THE GLOBAL CONTEXT: OPPORTUNITIES AND CHALLENGES

Global Opportunities: Increased Demand for Food and Other Agricultural Products

Population growth, rising incomes, changing diets, and the development of new markets for non-food agricultural products will offer great opportunities for the agricultural sector over the next several decades.[6] According to the United Nations, the global population is expected to reach 9.3 billion in 2050 (up from 6.9 billion in 2010) (UN Department of Economic and Social Affairs, 2011). This rise in

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[6] For an overview of the key trends, see Björklund *et al.*, 2009; de Fraiture & Wichelns, 2010; de Fraiture *et al.*, 2007; Foley *et al.*, 2011.

population will increase the demand for food. At the same time, income growth in the developing world is expected to heighten demand for meat, dairy, and other higher value (and higher water content) agricultural products, given that people tend to buy more food and seek more varied diets as per capita incomes rise (Kearney, 2010). As different types of foods become more widely available as a result of increased development, dietary intake of energy-rich foods with higher fat and protein, higher salt, and higher sugar contents (which also tend to require higher water consumption to produce) is also projected to increase (Kearney, 2010).

These trends could have significant implications for water use in agriculture. Some estimates project that annual crop water consumption would have to almost double to meet these growing demands (de Fraiture & Wichelns, 2010). These baseline estimates assume no further improvements in efficiency of water use. A more optimistic scenario — in which there were improvements in areas such as the water use efficiency of precipitation-fed and irrigated agriculture, reductions of waste in the food supply chain, and regional optimization of food production — suggests that crop water consumption would only need to increase by about 20 per cent (de Fraiture & Wichelns, 2010). Such differences illustrate the positive impacts that can be achieved by improving the sustainability of agricultural production.

Demand for non-food agricultural products can be expected to rise with the global increase in populations and incomes as well. Biofuels, which currently make up only about 2 per cent of the global crop area (de Fraiture *et al.*, 2008), offer one example. In recent years, technological advances have made the use of biofuels more feasible; governments and businesses have encouraged their uptake to achieve economic, strategic, and other objectives; and certain consumers have gravitated to using them for their perceived environmental benefits.[7] Consequently, use of biofuels has increased and could rise further in the immediate future, though the longer-term potential for, and appropriateness of, expanded biofuel production remains highly uncertain (Connor *et al.*, 2009). Other non-food agricultural product opportunities with growth potential include bio-based industrial chemicals and pharmaceutical products (AAFC, 2011a; Boehlje & Bröring, 2011).

Over the near to medium term, global population growth and an increase in affluence of emerging economies can be expected to lead to an ongoing, stable increase in demand for agricultural products of all types (de Fraiture *et al.*, 2007). These market drivers should create new opportunities for agriculture in Canada,

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[7] On the reasons behind the adoption of biofuels, see de Fraiture *et al.*, 2008; de Fraiture & Wichelns, 2010; Laan *et al.*, 2009; Ragauskas *et al.*, 2006.

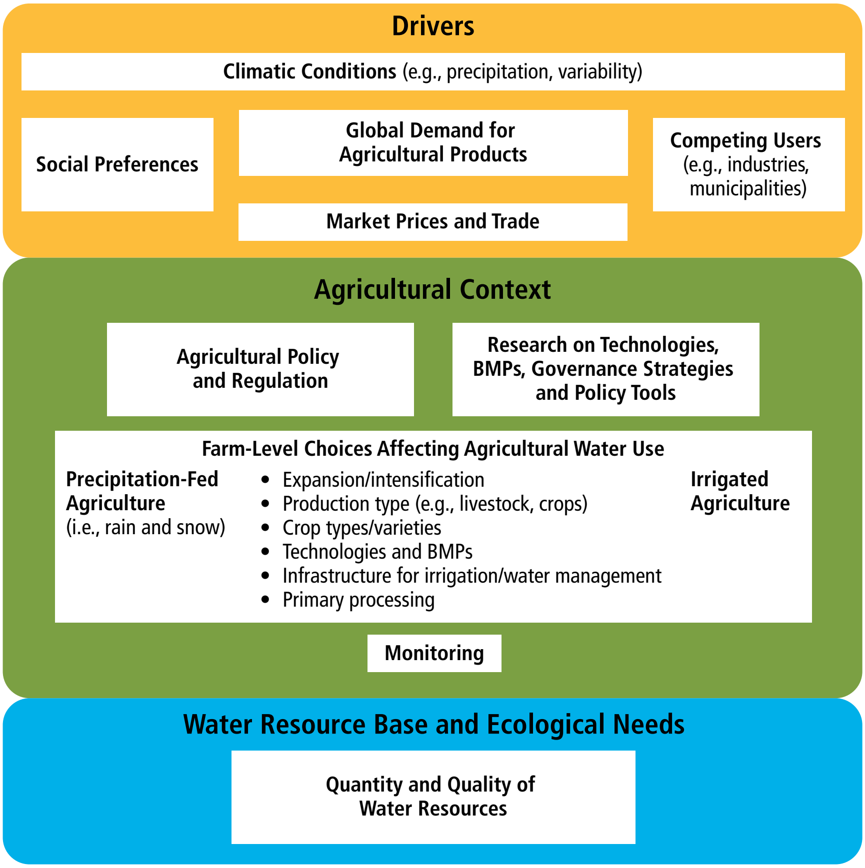

Figure 2.1

Conceptual Framework of the Domestic and Global Drivers Surrounding Agricultural Water Use

This figure illustrates a conceptual framework of the drivers and context of water use in agriculture. There are complex links between these drivers and components of the agricultural context. Both the drivers and agricultural context influence the health of the water resource base in terms of quantity and quality.

a significant economic sector that contributes to economic growth, job creation, and social well-being in rural communities (see Section 2.2); however, a number of important challenges need to be addressed to ensure that this sector can pursue the appropriate opportunities effectively.

Global Challenges: Growing Resource Pressures and Heightened Uncertainties

Intensifying competition for resources, changing market conditions, uncertainties in government and corporate policies, and climate change are among the many global challenges affecting sustainable management of water for agriculture. There are several areas in which additional science can be beneficial in understanding and overcoming these challenges.

Intensifying Competition for Land and Water

Among the greatest challenges facing agriculture around the world is the intensifying competition for resources such as land and water (de Fraiture & Wichelns, 2010; Godfray *et al.*, 2010). This is a challenge that is being confronted across many sectors as the world's population grows, incomes rise, economic development advances, and resources become scarcer relative to demand. Water is a key pressure point in this competition, particularly in areas of the world that are already water stressed. Under the combined pressures of population growth and climate change, water stress is also projected to increase in the coming decades. According to some estimates, as many as six billion people may be living in water-stressed areas by 2050 (based on a review of scenarios by Kundzewicz *et al.*, 2007).

Agricultural production is closely connected with water availability. However, the nature of water consumption in agriculture needs to be understood in an appropriate context. About 71 to 80 per cent of the world's cultivated land relies on precipitation (sometimes called rain-fed, though including both rain and snow)[8] whereas only 20 to 29 per cent is irrigation-fed (de Fraiture & Wichelns, 2010; Molden *et al.*, 2007b). This latter component is significant with respect to the competition for water because water withdrawn from aquifers, lakes, and rivers for irrigation (sometimes referred to as blue water) is normally subject to competition with other users such as industries, hydropower, and municipalities. Moreover, this blue water consumption tends to have a much greater impact on the local environment than precipitation-fed agriculture (green water) because of the ways in which irrigation can add to water stress by increasing the level of water consumption and changing environmental flows (Molden *et al.*, 2007b). Nevertheless, both precipitation-fed and irrigated agriculture have critically important roles to play in meeting the world's future agricultural demands (see Box 2.1).

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[8] For the purposes of this report, the Panel has opted to use the term "precipitation-fed" to better reflect the reality that much of agriculture in Canada is fed by a combination of rain and snow.

Box 2.1

Potential Contributions of Precipitation-Fed and Irrigated Agriculture for Improving Agricultural Productivity and Sustainability

As populations continue to grow and the effects of climate change are felt, both precipitation-fed and irrigated agriculture can contribute to productivity and sustainability. The extent to which any management practice or technology can be effective depends on numerous factors, including crop type, properties of the land, and other local conditions.

The productivity of precipitation-fed agriculture can be enhanced by improving water use efficiency, resulting in higher crop yields without expanding the area cultivated. For example, using mulching or conservation tillage can both decrease the amount of water that is unproductively lost by evaporation from soil and reduce surface runoff, thereby increasing the moisture available to the crop from the soil (for example, see Rockström *et al.*, 2010).

Although irrigated agriculture occupies up to 29 per cent of the world’s harvested area, it accounts for as much as 38 per cent of the gross value of production (de Fraiture & Wichelns, 2010). Many expect that, as populations grow, the climate changes, and consumption habits evolve, irrigated agriculture will play a larger role in food production worldwide (The World Bank, 2010). The advantages of irrigated agriculture are simple: higher crop yields and protection from climate variability, such as drought. The challenge is the potentially significant environmental impact of irrigation, with large quantities of water diverted to supply crops. Increased use of irrigation also contributes to, and reshapes, global flows of virtual water (Chapagain & Hoekstra, 2008) (Box 2.2). For example, agricultural products grown for export using irrigation in water-scarce regions may represent a movement of water from those regions to other parts of the world, including Canada. Additionally, as the proportion of global food production grown using irrigation increases, flows of virtual water will be transformed, with more of those flows based on surface water and groundwater sources relative to precipitation and soil moisture. Counterbalancing these concerns, the efficiency of water use on irrigated cropland can be greatly improved through better on-farm management and maintenance of irrigation systems, by using advanced technologies such as drip irrigation, and by recycling drainage systems. The potential alternative uses of such water should also be considered.

Box 2.2
The Concept of Virtual Water

Virtual water is defined as "the water that is used in the production process of an agricultural or industrial product" (Hoekstra & Hung, 2002). In the case of agriculture, this includes the water used in growing crops or maintaining livestock. How much virtual water is used in each case depends on how and where the product is produced. For example, as Hoekstra and Hung (2002) explain, producing a kilogram of grain that is precipitation-fed and grown in an agriculturally favourable climate will take about 1000 to 2000 kg of water. However, growing the same amount of grain in a country with less favourable climate conditions, such as high temperatures and limited precipitation, will take up to 3000 to 5000 kg of water.

Although often used for conceptualizing the virtual trade in water among regions or countries (Hoekstra & Hung, 2002; Konar *et al.*, 2011), the Panel believes that there are certain shortcomings in the concept of virtual water that warrant caution. First, the concept does not account for the water that would be used for maintaining the landscape in its natural state. On the Prairies, for instance, there is no significant difference in water consumption between dryland cereal grain growth and native grasslands (Armstrong *et al.*, 2008). Secondly, the concept implies that water that is not used in virtual import or export would be released for other uses. This is not necessarily the case, as agriculture can be the main alternative use to non-use (particularly in less populous regions) (Frontier Economics, 2008).

Changing Market Conditions

Changing market conditions are another source of uncertainty. While the long-term trend in global demand for most agricultural products will be positive for decades to come, market prices may not necessarily reflect those trends in the short- and medium-term. Recent global food crises have shown that the main concern for global agricultural markets is an increase in food price volatility rather than an absolute shortage in supply. Food price volatility is caused by a complex set of factors, including long-term decline in global food stocks, energy prices, exchange rates, resource pressures, agricultural trade measures such as export bans, weather shocks (extreme events and climate variability), and high levels of speculative activity in future markets (Heady & Fan, 2008; OECD-FAO, 2011).[9]

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[9] The increase in demand for biofuels was one of a number of factors that led to recent peaks in food prices. While studies conducted by IFRI show that the 2007-2008 food crisis was mainly caused by long-term systemic factors such as decline in stocks, rising energy prices, and decreased resilience to price shocks, increase demand in biofuels does emerge as a significant factor that could affect future food prices, unless policy measures are taken to prevent the displacement of food production through biofuels (Heady & Fan, 2008). Modelling exercises also show that new biofuel policies that include certain criteria for sustainable production may still lead to significant substitution effects in land use (Laborde, 2011). These substitution effects also have important impacts on water use (Harto *et al.*, 2010; Hoogeveen *et al.*, 2009) and emissions of greenhouse gases (Searchinger *et al.*, 2008).

The experience of recent crises has initiated discussion on a number of possible measures that, if implemented, could reduce food price volatility in the medium term. Some of these measures are aimed at increasing national and regional self-sufficiency in staple food production (The World Bank, 2010). If such strategies are successful, international trade in agricultural products and related opportunities to develop export markets could grow at a rate below that of general demand, with some reduction to opportunities for export-oriented production strategies.

In the short term, price volatility creates financial risks for farmers. Although farmers may benefit from high prices in some years, these gains are likely to be offset when prices collapse in other years. The uncertainty of revenues makes financial planning difficult and could reduce the willingness of farmers to invest in or focus on crops that are exposed to volatility. This could leave some market opportunities unexploited. Price fluctuations are part of the everyday reality of farming. Although a number of financial and policy mechanisms such as short-term credit,[10] crop insurance, or measures to buffer the impact of global prices are in place to assist farmers in addressing "normal" price fluctuations (Gilbert & Morgan, 2010), recent trends in food price volatility go beyond the range anticipated by these instruments. They could affect the financial stability of farmers and food processors in the medium term. This is a particular concern since investments in water management infrastructure and irrigation typically have a long time horizon and require stability for financial planning.

Uncertainties in Government and Corporate Policies

Another factor related to international market conditions is policy development in other countries that could affect, or even distort, international trade in agricultural products. The general impact of these measures is that they dampen or eliminate the transmission of international signals to domestic producers. This affects investment decisions aimed at exploiting new opportunities in international markets. Despite efforts in international trade liberalization, trade in agricultural products in many countries is still restricted through measures such as import tariffs or quotas (Gifford *et al.*, 2008a, 2008b). Furthermore, all international trade in agricultural products is regulated by international standards for plant and animal health and food safety, such as the standards for sanitary and phytosanitary measures endorsed by the World Trade Organization (WTO). In addition to these standards, individual countries may impose additional restrictions on imports of agricultural products. For instance, some countries may seek to restrict food imports and exports as a way of enhancing domestic food security at a time of

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[10] For example, AgriStability, AgriInvest, and AgriInsurance are the Growing Forward elements of the Business Risk Management Suite.

rising global food demand (Anderson, 2010a; Godfray *et al.*, 2010). Additional uncertainties may also arise from changes required by “sustainability indexes” and other standards imposed on farmers by a growing number of multinational food corporations (see Box 2.3).

Also of particular importance are regulations regarding products derived from genetically modified organisms (GMOs). Perceptions of the risks associated with GMOs and their products vary widely among countries. Many that are important export markets are currently revising their policies with regard to import restrictions and requirements for GMO-related products. These developments are relevant for the future demand of agricultural water use, since genetic modification may become a key tool for manipulating water demand from agricultural crop varieties. While the first wave of genetic modification focused on strategies to increase yields and resistance to pests and pathogens, future strategies will increasingly seek to expand the adaptability of crops to varying climatic conditions by increasing tolerance to heat, cold, and water stress. GMO-related import restrictions could have an impact on the portfolio of technologies available for export-oriented agricultural production strategies, including technology options that affect water use (Anderson & Jackson, 2012; Hewitt, 2010; Tangermann, 2010; Valetta, 2010).

Box 2.3
Implications of Sustainability Indexes for Agricultural Supply Chains

The consumer market can have a significant impact on agricultural water management practices, since companies can place requirements on farmers from whom they buy products. There are thousands of certification schemes/standards and voluntary sustainability initiatives worldwide. To a varying degree, they cover environmental, social, and economic indicators, including water conservation (Potts *et al.*, 2010).

Several large companies have adopted sustainability indexes as a marketing tool to provide brand recognition of their specific environmental goals. In some cases, retailers such as Walmart and Nestlé develop in-house sustainability measures that are used to select suppliers (Nestlé, 2010; Walmart, 2010). Third-party certification is also commonly used as a means to recognize and brand a “sustainable” product. An example is the Rainforest Alliance, which works with several retailers in Canada to provide certification for products such as coffee, tea, and cocoa (Rainforest Alliance, 2012). Business-to-business (B2B) sustainability programs that are not seen by

continued on next page

consumers are also used by companies such as Loblaws and McCain. These measures are used to ensure food safety, with certification being provided by third-party companies such as CanadaGAP and PrimusLabs.

Both retail and B2B types of indexes often include a series of rules or criteria to determine if conditions meet the requirements for sustainability (Genier *et al.*, 2008). While the introduction of sustainability measures is voluntary for the purchasing organization (e.g., Walmart, Loblaws), they become mandatory for producers. For most mainstream schemes, if farmers do not meet the conditions set, their goods will not be purchased (Genier *et al.*, 2008). As there are several different indexes with varying requirements, it can be a difficult and complicated process for farmers who need to comply with more than one set of measures. In addition, the indexes are often produced without considering contextual conditions, and therefore a producer can be deemed unacceptable for irrelevant reasons (Genier *et al.*, 2008).

The Panel believes that producers have a need for standards that are consistent, reasonable, and scientifically sound. Schemes or standards should be analyzed using a common language that compares their objectives and effectiveness (Potts *et al.*, 2010). An example of this work is being carried out under the auspices of the State of Sustainability Initiatives Project coordinated by a number of international bodies, including the International Institute for Sustainable Development and UNCTAD (Potts *et al.*, 2010).

Uncertainties Related to Climate Change

Climate change is also likely to pose increasing challenges for agriculture through changes to climate variables (e.g., temperature, precipitation, and CO_2 levels), increased occurrence of extreme events (e.g., floods, droughts, and heat waves), and other indirect effects (e.g., the spread of pests and diseases). How exactly, and to what extent, such developments will impact agriculture and water varies by location. While scenarios of future climate remain subject to considerable uncertainty, particularly with respect to local and regional precipitation (Kundzewicz *et al.*, 2007), it is now widely accepted within the scientific community that a warmer world will lead to an accelerated hydrological cycle with an expected global average increase in precipitation. However, some of the world's major agricultural regions can expect substantially less precipitation (IPCC, 2007; FAO, 2008). For example, already relatively dry areas of the Canadian Prairies may become more so as the temperature increases (Kulshreshtha, 2011). Simultaneously, climate variability and extreme events are also expected to increase (Kulshreshtha, 2011). Precipitation across the Canadian Prairies is already showing change, with a transition to more rainfall and less snowfall in the spring and fall, as well as an increase in the intensity and duration of major multi-day rainfall events (Shook & Pomeroy, 2012).

Regardless of the exact nature of future climate, climate change will likely complicate efforts to increase agricultural yields while simultaneously improving water use efficiency and protecting natural ecosystems (The World Bank, 2010). Increased frequency of floods and droughts is a particular concern, with dramatic effects on agriculture evidenced, for example, by the teleconnected Russian heat wave and Pakistan floods in 2010 (see, for example, Coumou & Rahmstorf, 2012), and, at the time of writing, the 2012 drought centred in the U.S. (NOAA, 2012a). Furthermore, changing and varying climate conditions can contribute to large short- and long-term shifts in the supply of certain products, leading to price changes that can be positive or negative for agricultural producers. To some extent, farmers have long faced this challenge; however, climate change would tend to accentuate this uncertainty (Kurukulasuriya & Rosenthal, 2003; Warren & Egginton, 2008).

2.2 THE CANADIAN CONTEXT: WATER, CLIMATE, AND ECONOMIC AND SOCIAL DIMENSIONS

The Importance of Agriculture for Canada

Agriculture is an important part of Canada's economy and society (see Box 2.4), making important contributions to GDP, exports, employment, food security, and the strength of rural communities. In 2010, primary agriculture alone produced $51.1 billion in gross farm receipts. It is also an important component of a much wider agri-food system, accounting for close to 2 million jobs (AAFC, 2011c; The Conference Board of Canada, 2011). Moreover, some 70 per cent of the food bought in Canada is supplied by Canadian agriculture producers (as cited by NRTEE, 2010a).

Though it is significant in all regions, the agriculture and agri-food sector also forms a larger share of the economy in some provinces compared with others (AAFC, 2011c). The national average contribution to provincial GDP is about 3.25 per cent, with the largest share in Saskatchewan (12.8 percent) and the smallest in British Columbia (about 1.8 per cent).[11] As shown in Figure 2.2, there are also significant regional differences in production. Grains and oil seeds, for example, are important for the agricultural economy of the Prairies, the dairy industry is relatively important for Quebec, and fruits and vegetables are important for British Columbia. As discussed throughout this report, these regional differences in

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[11] Based on 2011 data supplied by AAFC.

Box 2.4
A Profile of Agriculture in Canada

According to the most recent Census of Agriculture (2011), the Canadian agriculture sector can be characterized as follows:

- 205,730 farms, down 10.3 per cent since 2006;
- 160.2 million acres of total farm area, down 4.1 per cent since 2006;
- 87.4 million acres of land in crops, down 1.6 per cent since 2006;
- Farms with $500,000 and over in gross farm receipts account for 11.5 per cent of farms and 67.9 per cent of total gross farm receipts in 2011, up from 8.6 per cent of farms and 60.1 per cent of total gross farm receipts in 2006;
- 293,925 farm operators, of which 27.4 per cent are female;
- 48.3% of operators are aged 55 or over, with the average age at 54; and
- 3,713 certified organic operations in 2011, up from 3,555 in 2006.

(Statistics Canada, 2012)

production create different needs for water consumption and water management, and have significant implications for which sustainable management practices may be most appropriate to each regional context.

Canada's Water Resources

Water, and the ecosystems it supports, is among Canada's most valuable resources. Water is essential to all forms of life and is used in all sectors of the economy in some way. Thus, it is not surprising that Canadians generally recognize the importance of water. A 2011 Ipsos Reid survey of over 2,000 Canadians found that 55 per cent of respondents rated water as Canada's most valuable natural resource (compared with 15 per cent who chose agricultural land, 13 per cent who chose forests, 12 per cent who chose oil, and 4 per cent who chose another resource) (Ipsos Reid, 2011).[12] In the same survey, 41 per cent said they were "very concerned" about the long-term supply/quality of Canada's fresh water while another 39 per cent said they were "somewhat concerned" (Ipsos Reid, 2011).

Canadians have good reason to be concerned about the supply and quality of their fresh water resources. Droughts and water shortages are an ongoing challenge, while water quality issues and degraded ecosystems are pervasive. Moreover, approximately 70 per cent of the country's fresh water flows north whereas the

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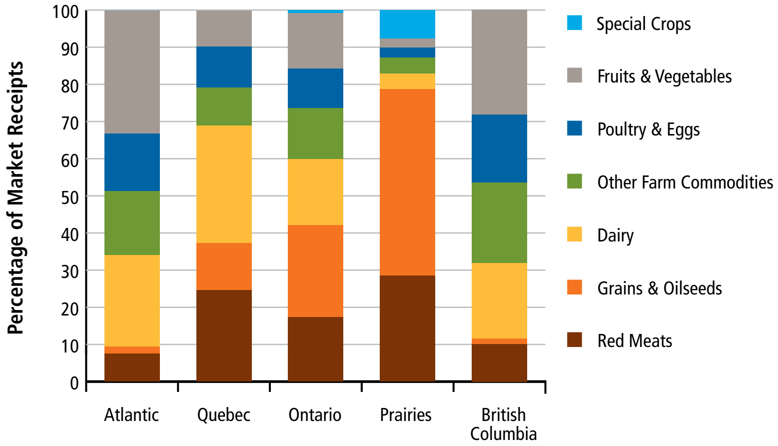
[12] Numbers do not sum to 100 due to rounding.



Data source: AAFC, 2012

Figure 2.2

Regional Market Receipts by Commodity Share, 2012

This figure illustrates the differences in the share of market receipts by commodity among agricultural producers in different regions of Canada.

majority of the population is located in southern portions of the country (Corkal & Adkins, 2008; Statistics Canada, 2010a). Available water resources are also distributed unevenly across the country and are under growing competition in some places. For example, comparing water use to the available streamflow reveals that areas such as southwestern Quebec, southern Ontario, portions of the interior of British Columbia, and parts of the Prairies are already experiencing pressure on water resources (NRTEE, 2010a).

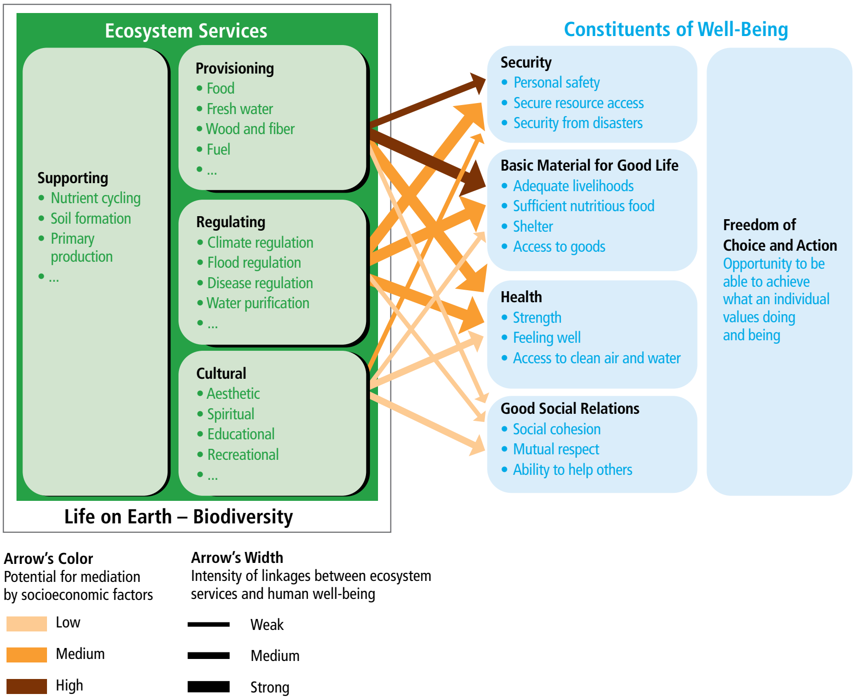
Water flows and groundwater levels support ecosystems and human populations. In terms of aquatic ecosystems, a particular concern is *environmental flows*, which are defined by the World Bank as the "quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to people" (Hirji & Davis, 2009). More generally, surface water and groundwater systems provide what are known as ecosystem services, which include — but are not limited to — water for people and animals, support for aquatic and terrestrial ecosystems, flood protection, navigation routes, and waste dilution and removal (see Figure 2.3). People use these ecosystem services to generate economic wealth, health, and well-being; however, in doing so, we may also harm ecosystem health (e.g., through overuse, diversion, or pollution) and impair the ability of ecosystems to produce such benefits (Millenium Ecosystem Assessment, 2005). The challenge is to ensure that water is valued and conserved in a way that reflects its full economic, environmental, and social value. Value is often accounted for only in terms of what can be produced by ecosystems; what is needed to sustain them is not considered (Millenium Ecosystem Assessment, 2005). These issues are discussed further in Chapter 6.

Water's Importance for Canadian Agriculture

Overall, agricultural activities account for about 10 per cent of gross water withdrawals in Canada, well behind thermal power generation and municipal and rural domestic use (NRTEE, 2010a). However, agriculture is the largest consumer of water in Canada, accounting nationally for 66 per cent of water consumed, though with important regional variations (NRTEE, 2010a).

Access to sufficient quantities of fresh water is essential to agriculture. In the case of precipitation-fed agriculture, precipitation forms one of the limits of crop and livestock production. The vast majority of Canada's crops are precipitation-fed, occupying 97.6 per cent of harvested area in 2006 (AAFC, 2011c). In some regions of Canada, irrigation is used to address deficits in the amount of available precipitation, increase productivity, and, in some cases, improve product quality. The prevalence of irrigation varies widely across Canada. British Columbia has the largest proportion — 20 per cent — of its cropland area irrigated. Alberta has the largest irrigated area, representing 64 per cent of the national total of irrigated area (AAFC, 2011c). As discussed in Chapter 3, competition between agriculture and other uses of water can be a limiting factor for the expansion of agricultural production.

Agriculture can also have other impacts on the environment and human well-being. These impacts may be positive or negative, depending on the local conditions, the technologies that are employed, and the management practices that are adopted (Power, 2010). For example, a well-managed farming operation will try to limit negative effects on water or other aspects of the environment and may offer benefits for a range of ecosystem services (Power, 2010). However, agriculture can negatively affect aquatic ecosystems as a result of change in land use (e.g., loss of natural habitat through conversion of wetlands to farmland) and water use, pollution, and erosion. Sources of contamination include pesticides and nutrients



Adapted from Millenium Ecosystem Assessment, 2005

Figure 2.3

Linkages between Ecosystem Services and Human Well Being

This figure shows the linkages between ecosystem services and the constituents of human well-being, illustrating how ecosystem services provided by the environment are intrinsically linked with human well-being.

(including nitrogen and phosphorus) from fertilizer runoff, and waterborne pathogens and endocrine-disrupting substances from animal waste (Corkal & Adkins, 2008). These contaminants can impair both the quality of drinking water and the health of ecosystems. In addition, poor quality water can impact agricultural productivity, affecting animal health, pesticide effectiveness, and the efficiency of cleaning operations (Corkal & Adkins, 2008). As discussed further in Box 2.5, these are but a few examples of the interconnections between land use and water management. Specific challenges and opportunities with respect to land use and water management in agricultural landscapes are discussed throughout this report, including the challenges posed by competing uses (Chapter 3) and land use changes (Chapter 4), together with the opportunities offered by conservation agriculture and BMPs (Chapter 4), technological innovations (Chapter 5), and governance strategies (Chapter 6).

Box 2.5
The Link between Land Use and Water Management

Land use and water management are intimately connected. Human activities have profoundly changed the land on which we live, and land use and land management changes affect the hydrological processes that determine flood hazard, water resources (for human and environmental needs), and the transport and dilution of pollutants (Wheater & Evans, 2009). At a fundamental level, the hydrological processes that determine the rate and timing of surface runoff and groundwater recharge, and the associated water quality, depend on the nature of the land surface. A simple example is urban development. Replacement of a permeable soil land cover by a roof or paved area removes soil water storage from the hydrological cycle and increases overland flow, potentially increasing flood peaks in rivers and decreasing low flows. Agricultural land management change is more complex; for example, crop type will influence evaporation and tillage practices may affect snow accumulation and runoff processes. Whether land is used for residential, industrial, or agricultural purposes also has a direct impact on the amount of water that will be withdrawn and consumed, and the quantity and quality of water that will be returned to surface water and groundwater bodies. For each of these reasons, land use and water management need to be considered in relation to one another.

Canada is fortunate to have access to water resources that have the potential to sustain a strong agricultural sector. However, continued access to adequate quantities of water of appropriate quality cannot be taken for granted. The continued viability of the agricultural sector as well as its ability to take advantage of current and emerging global opportunities will depend on the resilience and adaptability that Canadian farmers have honed and displayed over generations and the extent to which systems for water management and governance are strengthened. This is particularly important in light of the changing public perceptions of agriculture (Box 2.6) and its “social licence to operate.”

Box 2.6
Perceptions of Agriculture

The attitudes of Canadians towards farming and agricultural issues have not been extensively researched. Likewise, there are few available data on the view that farmers have on the policy framework and emerging issues facing the industry. Nonetheless, recent surveys suggest some important national trends. A 2010 online survey of Canadians' view of agriculture in Canada commissioned by the Ontario Farm Animal Council (OFAC) provides one example. The survey, conducted by Ipsos-Reid, showed that 57 per cent of the respondents had a positive impression of Canadian agriculture (OFAC, 2010). The results suggested that farmers have a high rate of public credibility on food and farming issues, ranking second just behind veterinarians (OFAC, 2010). Furthermore, according to a Farm Credit Canada Survey conducted in 2011, 82 per cent of Canadian consumers also "agreed that the agriculture industry is doing well at supplying the population with safe and healthy food" (Farm Credit Canada, 2011). Other surveys, however, have suggested that a portion of the population views agriculture as a significant polluter (Jones, 2006). As Sadler Richards (2003) puts it, "gone are the days when farming was considered an idyllic lifestyle with benign environmental impacts." This represents a significant dichotomy between the positive impression societies have of agriculture and their view of agriculture as a significant polluter.

Climate Change

Even under normal conditions, the Canadian climate has large variations geographically, seasonally, and inter-annually. One consequently cannot use highly aggregated climate data, such as national values, for agriculture. Farming practices, infrastructure, production systems and crops are generally adapted to an area's average climatic conditions. Changes away from a particular climatic state will result in pressure to adjust current practices to maintain productivity (Gornall *et al.*, 2010).

Recent history provides some evidence for what climate change might mean for Canada. Climate change has already resulted in an increase in mean temperature in Canada and is likely affecting local precipitation patterns (Zhang *et al.*, 2011). When one considers a period that spans multiple decades, there is evidence of change in overall moisture levels. For example, Mekis and Vincent (2011) illustrated that there has been a general increase in precipitation over the last few decades in some parts of the country. On the other hand, trends in one measure of surface water availability (which also considers temperature and evaporation) known as PDSI (Palmer Drought Severity Index), infer a general drying trend over much of Canada (Dai *et al.*, 2004). Warmer temperatures have led to increased evaporation that creates a drier surface, and therefore counters the increase in precipitation. In addition, the loss of snowcover due to the transition from snowfall to rainfall over much of the country has had implications for agricultural snow management practices on the Prairies in particular (Shook & Pomeroy, 2011, 2012) and for small scale runoff that provides water for livestock (Pomeroy *et al.*, 2012). Furthermore, the decline in Rocky Mountain snowpack (Brown & Mote, 2009; Mote *et al.*, 2005) has had important implications for the supply of water for irrigation and the continued efficacy of water management structures and systems in the Prairies (see, for example, Centre for Hydrology, 2012).

Climate change is projected to have major impacts on water availability for agriculture in most if not all parts of the country, but these impacts will vary with local climatic, geographic, and agricultural conditions in response to a number of interacting factors. Three types of impacts on water availability can be distinguished: (a) impacts through local climate change; (b) impacts through remote climate change; and (c) impacts through increases in climate variability.

Impacts through local climate change are primarily related to the effects of increasing temperatures and changes in precipitation patterns. One of the most important impacts is the effect on water storage in soil and surface waters. Changes in precipitation patterns form the main local driver of change in water availability, but they are also one of the most difficult to predict because of interdependencies with changes in atmospheric circulation, as well as local conditions that include soil moisture. Current models cannot consistently account for all of these interdependencies (Schiermeier, 2010). Reduced snowfall and earlier snowmelt runoff will also affect soil moisture levels and may lead to inefficiencies in water use as runoff occurs at times that are unsuitable for agricultural water management (Gornall *et al.*, 2010). At the same time, increases in temperature will lead to increased water use through evapotranspiration, unless the region is already affected by a lack of soil moisture due to drought (Gornall *et al.*, 2010; Miller *et al.*, 2000). Indirect impacts include increased water use through intensification or expansion of agriculture as increased temperatures allow the cultivation of different types of crops, thereby expanding the growing season, expanding the area under irrigation, and expanding the northern boundary of agriculture (Gornall *et al.*, 2010; Olesen *et al.*, 2007).

Impacts through remote climate change will be most relevant for irrigated agriculture, depending on rivers fed by snowmelt in upstream mountainous regions. Reduced peak flow, spring-summer flow, and changes in timing of peak flow events because of earlier spring snowmelt affect water availability for uses downstream (IPCC, 2007; Stewart *et al.*, 2005). Reduced water levels in river systems that rely on snowmelt can have an even more dramatic effect on irrigated agriculture (Mote *et al.*, 2005; NRCan, 2004; Stewart *et al.*, 2005).

Impacts through increases in climate variability will be observed through many types of extreme meteorological events that can also affect agriculture (NRCan, 2004). These events include heavy precipitation, hail, wind, and frost as well as their timing. In turn, heavy precipitation events or long wet periods can lead to flooding. There is also concern that climate change may lead to catastrophic droughts over the Prairies (Bonsal *et al.*, 2012). Higher expected temperatures with climate change are likely to accelerate evaporative processes and enhance the drying of the surface (see, for example, Dai, 2011). Some scenarios suggest the possibility of droughts occurring in the Prairies later in this present century that would be more severe than droughts experienced in the 20th century (Bonsal *et al.*, 2012). The effect of drought on agriculture is generally dramatic (Wheaton *et al.*, 2008). Many of the worst disasters affecting Canada are linked to drought, predominantly in the Prairies, with many of the effects coming from agricultural losses (Bonsal *et al.*, 2011).

Forecasting water availability is difficult to predict now, yet climate change poses even greater challenges for the ability to make accurate predictions about future climate conditions in Canada. The implications of a changing climate are expected to have far-reaching effects, and scenarios remain highly uncertain. Factors that complicate predicting the impacts of climate change on water resources include:

- The high variability of climate variables (such as precipitation), in terms of location and time of year (which is inherent to the Canadian climate system) makes it difficult to always identify long-term trends in precipitation patterns that occur at local or regional scales. In addition, in a warming world, an increase in precipitation extremes (both dry and wet) is expected. Therefore, trends of precipitation amount, for example, may mask the more subtle changes that are underway.
- Extreme weather events arise at least in part through complex interactions with large-scale atmospheric circulation systems and long-term cycles that are not well understood, making it difficult to predict their likely future (Mladjic *et al.*, 2011; Roy *et al.*, 2011).

- Current models do not adequately account for critical interactions between the surface and the atmosphere (Barrow *et al.*, 2004). Many precipitation events are fed at least partially from surface moisture conditions, which in turn depend on precipitation. This feedback effect must be adequately incorporated into models and tools used for predicting precipitation trends at local or regional levels.
- Similarly, there is a need to better understand large-scale storm processes. Szeto *et al.* (2011) recently showed that a catastrophic rain event over the southern Prairies in June 2002 was accentuated because of the prevailing drought conditions. Current models do not have the spatial resolution that is needed to account for internal storm processes and feedback that lead to such catastrophic events and have major impacts on agriculture and water availability.
- The prediction of drought, as well as other extremes, is also complicated by the limitations of modelling and monitoring. Bonsal *et al.* (2011) note the need for improved downscaling methods for the application of climate model data to assess future changes to drought-related parameters (see also Chun *et al.*, 2012; 2012, in press), as well as the identification of regions in Canada that are projected to be particularly susceptible to increased frequency and/or intensity of droughts. Furthermore, there is a need for better methodologies to include satellite and ground-based remote sensing for drought monitoring and management; a total water supply database; and improved integration of global and regional climate models with distributed hydrological models (Bonsal *et al.*, 2011).

Overcoming the many challenges of improved climate prediction requires a Canadian effort that is also linked with international ones. It is impossible to appropriately predict the climate at national, regional, and local levels if the global predictions forming the basis of this exercise are wrong (Taylor *et al.*, 2012). Current estimates of future global climate display a wide range of possible scenarios (Maslin & Austin, 2012) and this situation needs to be addressed in tandem with efforts focused on our improved capability to understand and manage our own climate-related issues. Canada benefits from, as well as contributes to, such international efforts.

Investing in research to understand climate change and variability, in order to improve predictions in particular, is essential for helping governments, agricultural producers, and other stakeholders make effective management decisions. This may be particularly important for future opportunities as well, as global climate change could also impact export markets for Canadian agriculture. Climate change will make many arid countries drier, and many of these countries already import a significant proportion of their food (The World Bank, 2010). In fact, several global scenarios project that developing countries would need to increase their net cereal imports by 10 to 40 per cent as a result of climate change (Fischer *et al.*, 2005). This would potentially result in the creation of new markets for Canadian agricultural products. However, any decisions to increase agricultural production or produce a different type of agricultural product for export would undoubtedly affect water consumption as well, making it critical to understand the current and future state of water resources.

Water Governance and Management in Canada

In broad terms, *water governance* refers "to the range of political, social, economic, and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society" (Global Water Partnership, 2002). In contrast, *water management* describes the operational activities undertaken to monitor, protect, and regulate water resources and aquatic ecosystems (Alberta Environment, 2008; Bakker, 2007b). In simple terms, water governance establishes the rules within which water management takes place (Rogers & Hall, 2003). It needs to consider the people and organizations involved, their roles and their relationships, and the formal and informal institutions through which decisions are made.

Water governance in Canada is extremely complex due to the way Canada's constitution divides responsibility for water, the large number of actors involved, and the evolution of the decision-making process. Responsibilities for many key functions are divided — and sometimes shared — among a host of actors including international bodies; federal, provincial/territorial and municipal governments; non-government organizations; and other stakeholders (Bakker & Cook, 2011; Environment Canada, 2010d; NRTEE, 2010a) (see Chapter 6).

Effective water governance is critical to the success of agriculture. For example, unclear rules regarding who can use water and inefficient decision-making systems create risks and uncertainties for farmers (see discussion of governance issues in Chapter 6). At the same time, agriculture in Canada occurs on enormous tracts of private land. Canadian farmers are therefore important to the success of water governance and water management. However, many of the changes needed to improve both water management and water governance in ways that enhance agriculture's ability to respond to threats and take advantage of opportunities cannot be made solely within the agricultural sector. For instance, agriculture's viability depends in part on effective systems for allocating water — but responsibility for water allocation in Canada's provinces normally lies with environment ministries and departments rather than with those responsible for agriculture (de Loë, 2009).

The Social Dimension: Values in Water Management Decisions

An essential question for decision- and policy-makers is how to integrate various value-based considerations into decisions about water. Economic growth, environmental needs, and social preferences are all connected to using and preserving water resources. Water has economic value as an input for industrial processes, energy production, and agricultural production; it provides essential services for the environment, sustaining terrestrial and aquatic ecosystems; and it has value to various groups in society, in terms of its cultural and spiritual value as well as the aesthetic, recreational, and intrinsic value that may be attached to the ecosystems supported by water. Access to clean water is, of course, essential to human and animal life — making it, in a sense, invaluable.

The nature of water resources creates a number of inter-related challenges for society. Water resources often possess many of the classic characteristics of a common pool resource: non-exclusive accessibility, potential for externalities (external costs), and rivalry among users.[13] Given that water is necessary to sustain life as well as integral to many economic and social uses, access to water has come to be perceived as a "right" that is typically provided for free or at nominal costs (Cosgrove & Rijsberman, 2000a). This allows the public to benefit from the many activities and uses that are sustained by water resources. In certain places, water is both widely accessible and runs through multiple private properties. This makes it difficult to exclude people from accessing or affecting water in various ways (Aylward *et al.*, 2010; Perman *et al.*, 2011).

Because of these non-exclusive characteristics, water tends to be used in a way that mainly reflects its value as an input to production. Impacts on others, in the form of externalities, are not normally incorporated into the price or use of water, particularly in the absence of regulations or incentives to the contrary. A standard example is that of a water source that is polluted by industrial use: the value of the industrial output can be captured by the owners of the industrial production, while the costs of the pollution can be passed on to others. Another example is extracting water for agricultural irrigation, which will produce value for the farmers and local community, but may not take into account the flow requirements needed for other downstream users or the local ecosystem (Aylward *et al.*, 2010).

The importance of water, its non-exclusive nature, and the potential for externalities are among the reasons why regulations and incentive structures have been created to govern and manage water resources. As long as water is abundant and the

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[13] On the nature of common pool resources, see Perman *et al.*, 2011.

competing pressures on water resources are not overwhelming, regulatory structures can be created to manage resources in ways that do not unduly impinge upon most users' enjoyment of the common pool resource and its benefits. However, as water resources become scarcer and the competition for them intensifies, the challenges of managing these resources to meet the potentially competing (or rival) needs of users become more acute (Burchi *et al.*, 2009). Increasingly, choices need to be made about what uses to permit and which users to prioritize, as well as who should bear what costs associated with management decisions regarding allocations and conservation. This leads to a further complication: as a common pool resource essential to many activities, there are typically multiple stakeholders with various claims and social preferences to consider in making these types of management decisions.

These characteristics of water have profound implications for the agricultural sector. Agriculture is only one sector among many in Canada that needs access to water, and whether or not it has continued access depends not only on factors such as climate change and demands from competing sectors, but also on its social licence to operate. For example, historically water for the environment was not a broad social priority in Canada. Today, Canadians expect healthy aquatic ecosystems. Thus, in some parts of the country, the environment has become agriculture's most important competitor for water.

Agricultural Policy and Regulation

Agricultural policy, both federal and provincial, has a major influence on decisions that affect water use in agriculture. At the federal level, Canada has been pursuing an export-oriented strategy aimed at establishing an agricultural sector that is internationally competitive. This increases the influence of global market prices on production strategies, and will likely lead provinces and farmers to develop strategies that take advantage of the opportunities arising out of growing international demand. At the same time, the objective of agricultural policy is to bring agriculture in line with the interests of the public and to address environmental, economic, and social concerns. In this sense, the policy framework can act to encourage the development and adoption of water conservation practices and discourage practices that have adverse impacts on sustainable water management. Over the past decade, the Canadian Agricultural Policy Framework (APF, Growing Forward)[14] has placed increasing emphasis on proactive risk management through programs directly available for farmers. These programs can help farmers overcome barriers for investment and provide options to hedge certain risks. In addition, policy

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[14] See http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1200339470715.

frameworks can provide funding for targeted programs, such as the Saskatchewan Farm Ranch Water Program[15] and the Alberta Water Management Program,[16] which encourage the development of long-term water management plans.

While the priorities for the next agricultural policy framework (Growing Forward II) are still under development, one of the components under discussion would allow for the development of place-based integrative approaches for "tailoring activities […] to regional or local circumstances and challenges," enable stakeholder involvement and "target environmental actions while at the same time addressing challenges and coordinating actions at broader scales over common landscapes or geographic areas."[17] These approaches could include the development of integrated water management strategies that take into account the needs of agriculture as well as other competing uses, while ensuring sustainable water management in the long run.

Human Resources/Skills Development

A progressive agricultural sector requires progressive thinking and a highly educated workforce. There are opportunities to assess future human resource/skills needs for the sector and meet these needs through the enhancement and development of academic and workplace training programs. Effective monitoring and management of water resources used for agriculture requires knowledge and expertise that will also lead to optimization of use, greater use efficiency, innovation, and capitalization of market opportunities.

In Ontario, for example, the agriculture and agri-food sector is an important component of the economy, generating an estimated $38 billion of GDP (excluding retail and food service) (JRG Consulting, 2012). This includes farming, agricultural supply and inputs, and farming service industries including financial services. It also includes farm produce processing and further food processing and manufacturing. The employment base for this sector in Ontario is over 200,000, excluding food distribution, retailing, and service. Highly qualified individuals with the necessary skill sets within sector businesses not only contribute to the success of their organizations, but to the success of the sector as well. A robust interview-based study of the sector conducted in late 2011 showed that 60 per cent of employers in the sector preferred to hire employees with formal training in agriculture and

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[15] Saskatchewan Farm Ranch Water Program, see http://www.agriculture.gov.sk.ca/Default.aspx?DN=f5474b70-dbdf-4e44-8b1f-cd4ebfb1c516.

[16] Alberta Water Management Program, see http://www.growingforward.alberta.ca/ProgramAreas/EnhancedEnvironment/WaterManagement/WaterManagementDetail/index.htm.

[17] AAFC innovative approaches program, see http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1292522946065&lang=eng.

food (JRG Consulting, 2012). Employers in the sector project a 10 to 20 per cent increase in demand for new hires over the next few years. The study also revealed that the requirement for formally trained graduates (at diploma, undergraduate, and graduate levels) is substantively above current supply levels in Ontario, signalling an urgent need for significant program recruitment and expansion efforts (JRG Consulting, 2012).

2.3 RESPONDING TO OPPORTUNITIES AND CHALLENGES: ADAPTIVE MANAGEMENT

In the face of uncertain futures, it is likely that new approaches to policy and management will be needed, with potential implications for governance. Lempert and Schlesinger (2000) discuss the limitations of traditional prediction-based policy, in which an optimum policy is identified by associating likelihoods with multiple, plausible scenarios of the future. They argue that in the face of complex problems, subject to high levels of future uncertainty, such analyses are inappropriate, because (a) the concept of an optimum policy assumes a single, rational decision-maker, whereas society contains a multitude of actors, each with different expectations about the future, and (b) optimum policies can be "brittle" in the face of the unexpected (e.g., high consequence, low probability events). They suggest that society should rather seek strategies that are robust (i.e., insensitive to uncertainty about the future), and that adaptive decision strategies can be a robust response to uncertain climate futures. Similarly, but in a different context of flood risk management, Sayers *et al.* (2012) also argue that adaptive management can provide robust decision-making under uncertainty. Camacho (2009) notes that fragmented governance is poorly equipped to deal with climate change, and suggests that an adaptive governance framework is adopted in which legislators require agencies to systematically monitor and adapt their decisions and programs.

Adaptive management thus offers one approach for responding to the opportunities and challenges of the agricultural sector. Developed over the past several decades with contributions from fields such as business, experimental science, systems theory, and industrial ecology (NAS, 2004a; Williams, 2011), adaptive management seeks to employ iterative learning to achieve better understandings of resource systems (or systemic challenges) and improve management outcomes based on those understandings (Williams, 2011). Adaptive management moves beyond ad hoc trial and error methods by adopting a structured approach that continually incorporates new information into management decisions, thereby allowing decision-makers and stakeholders to adjust their actions accordingly to achieve better results (Allen *et al.*, 2011; Williams, 2011). It is applied in range of fields such as natural resource management (Stankey *et al.*, 2005), business strategy (Hope, 2006), and public health (Hess *et al.*, 2012).

Although there are many specific systems of adaptive management, some aspects are common among them. These include the management objectives that are regularly revisited and accordingly revised; the development of a model or models of the system being managed; the existence of a range of management choices; the monitoring and evaluation of outcomes; the mechanisms for incorporating learning into future decisions; and the collaborative structures engaging stakeholder participation and learning (adapted from NAS, 2004a). The Panel's observations on the potential contributions of adaptive management to sustainable management of water for agriculture are discussed in more detail in Chapter 3 and in the report conclusions.

Review of Key Findings

- Over the next several decades, population growth and rising world incomes will generate tremendous opportunities for agriculture in increased demand for food and other agricultural products. At the same time, rising incomes are also likely to generate increased demand for higher value and more water-intensive forms of food such as meat and dairy products.
- To maximize the opportunities presented by these developments, the risks and uncertainties connected with changing market conditions, heightened competition for resources, climate change, and other factors will need to be managed carefully in order to ensure the sustainability of the Canadian agriculture sector.
- Investing in research to improve understanding of climate change and variability will be particularly important for helping governments, agricultural producers, and stakeholders make effective management decisions.
- The extent to which threats can be addressed, and opportunities exploited, depends to a large degree on the extent to which a solid foundation for sustainable water management is established. Effective governance is an essential part of this foundation.
- Adaptive management offers a useful framework for responding to these opportunities while mitigating risks and managing uncertainties.

3

Knowledge Inputs for Management Decisions: The Quantity and Quality of Canada’s Water Resources and the Needs for Monitoring, Modelling, and Adaptive Management

- Water Management for Agriculture in Canada
- Issues in Water Quantity: Water Availability and Competing Uses
- Issues of Water Quality: Nutrients, Pesticides, Pathogens, and Other Risks
- The Need to Inform Water Management Through Information on Water Quantity, Usage, and Quality
- The State of Water Quantity and Quality Monitoring in Canada
- The Role of Modelling, Forecasting, and Adaptive Management

3 Knowledge Inputs for Management Decisions: The Quantity and Quality of Canada's Water Resources and the Needs for Monitoring, Modelling, and Adaptive Management

Overview

As the pressures on water quantity and water quality increase in several regions across Canada, the agricultural sector, in collaboration with other water-intensive sectors, needs to work towards managing water use and consumption on a more sustainable basis. Managing water resources effectively requires adequate information on water availability, usage, and quality, all of which have significant current deficiencies with respect to monitoring and the availability of integrated data sets. An integrated water and climate monitoring and forecasting capability in Canada would provide for better risk management for agriculture, particularly in the light of unprecedented hydrometeorological non-stationarity due to climate change. Emerging research in modelling, forecasting, and adaptive management can all play important roles in the identification and management of risks.

Understanding water quantity and quality is essential to the success of the Canadian agriculture sector. Agriculture depends on reliable access to a sufficient quantity of good quality fresh water for activities such as crop irrigation and livestock production and on the occurrence of precipitation (and associated soil water management) for dryland agriculture. At the same time, agricultural development can have a large effect on water availability and quality (Foley *et al.*, 2005). As agricultural production intensifies, these pressures on the environment become of increasing concern. However, they do not exist in isolation. Around the world, increasing population, urban expansion, industrial development and economic growth — in addition to agricultural intensification — are generating increasing pressures on land and water resources, and environmental quality. Hence, where adverse effects are observed, these are often the result of diverse influences, from multiple sectors of the economy. To better guide sustainable management of water for agriculture, it is critical that these effects are well understood.

This chapter examines the state of water resources for agriculture. Section 3.1 begins by defining the context and objectives of water management for agriculture. Section 3.2 examines issues of water quantity, while Section 3.3 analyzes issues of water quality. Section 3.4 then continues with a summary of the need for information on water quality, water quantity, and water use, leading into the discussion of the state of water monitoring in Section 3.5. This discussion illustrates that as the pressures on water quantity and water quality increase in agricultural regions across Canada, agriculture and other sectors will need significant improvements in measurements to work towards managing water use and consumption on a more sustainable basis. The Panel feels that an integrated water and climate monitoring and forecasting capability in Canada would provide for better risk management in agriculture, and is of particular importance in the light of unprecedented hydrometeorological non-stationarity due to climate change. As part of such an approach, it also notes that the use of modelling, forecasting, and adaptive management can assist in the identification and management of risks. The research needs in these areas are examined in the concluding section of the chapter (Section 3.6).

3.1 WATER MANAGEMENT FOR AGRICULTURE IN CANADA

As explained in Chapter 2, discussion of water resources for agriculture must distinguish between (a) water withdrawn from rivers, lakes, reservoirs, and groundwater for irrigation, intensive livestock activities, and other farm uses which may compete with other water users; and (b) the water needed for dryland agriculture, which is fed by natural precipitation, as either rain or snow, and which may include redistributed snow using snow management techniques.[18]

Managing Water Resource Systems

An important characteristic of blue water use is that it is one of a set of competing demands for water resources, which in most parts of Canada will be managed at the scale of a river basin or groundwater aquifer, by provincial governments (governance aspects of water management are discussed in Chapter 6). Surface water resources include rivers, lakes and reservoirs, the latter providing artificial storage of river flow and local runoff so that water uses can be maintained when demand exceeds that which can be sustained by the natural system. Reservoirs typically balance seasonal variability of flow, but if large, can accommodate inter-annual variability. Reservoirs generally have multiple uses, such as public water supply, irrigation, industry, hydropower, recreation, and flood relief, which often represent competing demands. For example, high reservoir levels are desirable for hydropower production and security of supply; low reservoir levels are needed to reduce flood risk. Additional operational constraints may include the need to protect habitat and the management of river ice. The management

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[18] While it is common to discuss large scale water management using green and blue water concepts, the Panel recognizes that these are interlinked aspects of the hydrological cycle in Canada. For example, precipitation to a field or blowing snow can provide the source of either green or blue water, so application of these concepts for small scale water management is problematic in some cases.

of surface water resources typically involves optimizing the operations of water resource systems that involve multiple reservoirs and lakes, and large numbers of water users, with diverse and often conflicting needs in terms of flows and timing (including the need to maintain environmental flows to ensure healthy ecosystems and in some cases the need to dilute effluent discharges from industry or urban centres). For complex water resource systems, optimal management requires the use of mathematical models of the water resource system, and efficiency can be greatly enhanced by accurate forecasting of river flows.

Groundwater resources are typically more localized in spatial extent, but equally require management to balance the available aquifer storage with multiple competing needs. Sustainable management of groundwater requires balancing long-term recharge with long-term demand, but estimation of groundwater recharge is often complex and uncertain (Ng *et al.*, 2010). A further complication with groundwater resources is that some groundwater contaminants tend to persist for long periods (e.g., years to decades), so aquifer protection is an important management responsibility (Schmoll *et al.*, 2006). The extent of groundwater interactions with surface water systems varies greatly, but where the systems are closely coupled, groundwater must also be managed to minimize damage to surface water and aquatic ecosystems.

It can be seen that the management of blue water for agriculture is one aspect of the management of a complex water resource system, in which competing demands must be balanced through a process of governance, according to applicable legal frameworks. The Panel observes there are technical issues that require: (a) a high level of understanding of the hydrological systems that determine the available water yield and its variability; (b) data to support planning and operational management (e.g., hydrological data, and also of the climate variables that drive the hydrological cycle), as well as water demands; (c) accurate models for river flows and groundwater levels, including effects of water withdrawals and operational management decisions; and (d) a capability for forecasting river flows (and in some cases, groundwater levels). There are complex governance issues to be addressed and societal factors that are involved as well, including, for example, perceptions of the importance of environmental flows and social licence to operate for agriculture. As pressures on available water resources increase across Canada, attention is turning to the need for hard choices between alternative uses, and the role of economic instruments. The Panel notes that in the face of population and economic growth and rapid environmental change, water resources management is facing unprecedented challenges. Traditionally, water planning has used historical data as a basis for predicting the future. However, it is now widely accepted that under the changing climate, the past is no longer an adequate guide to the future (Milly *et al.*, 2008), and hence that new approaches to the management of uncertain futures are needed. This theme is examined again in Section 3.6.

Managing Water On-Farm

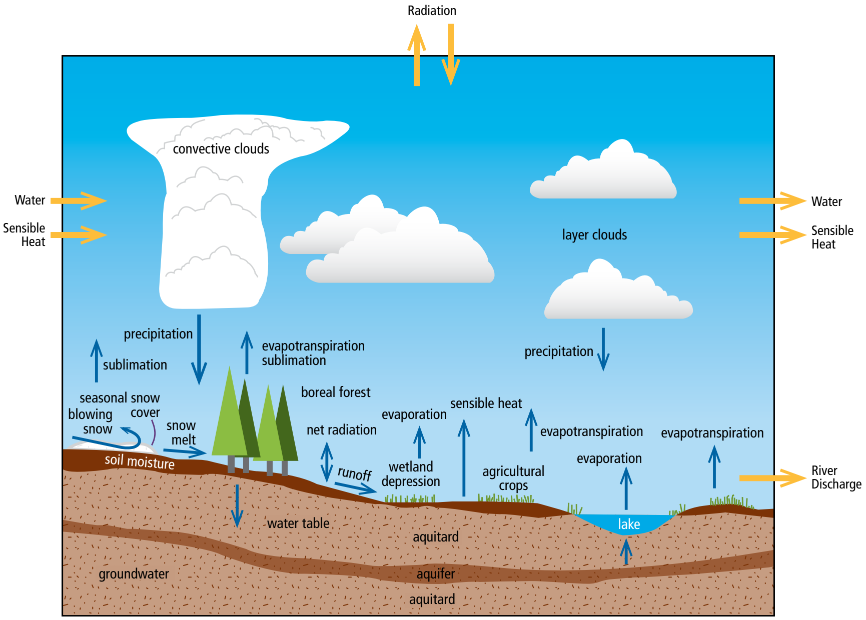
As noted in Chapter 2, while irrigation is a dominant consumptive use of blue water (both globally and regionally within Canada), precipitation-fed agriculture is the predominant form of agricultural land use in Canada. In both cases, a critical element of agricultural production is the management of water on-farm. Specific aspects of agricultural water management, related to land management practices, irrigation and drainage, and BMPs, are discussed in more detail in Chapter 4.

Water for agriculture on the farm can be stored as a solid, liquid, or vapour. Solid storage is in the seasonal snowpack lying over agricultural fields, and in seasonally frozen soils that occur over much of the Prairies and other agricultural zones. Liquid storage is as droplets in clouds, groundwater, soil moisture, and surface storage in depressions, ponds, wetlands, streams, lakes, and reservoirs. Vapour storage is in the atmospheric air mass. The time over which water may be stored for an agricultural setting depends on its phase: vapour for hours to days, liquid for hours to years, and snow/ice for seasons to years.

The flow of water between land surface, subsurface, ocean, and atmosphere is called the hydrological cycle, which is coupled to the flow of energy. Radiant energy from the sun and atmospheric energy carried by air masses are the major inputs to the land surface. The change of state (latent heat) when water evaporates from a crop or open water surface is an important consumer of that energy, together with energy transferred back to the atmosphere (sensible heat) (Figure 3.1). The hydrological cycle in Canada is remarkably seasonal, being dominated by snow and ice throughout the winter, thaw and runoff in spring, and rainfall, evaporation, and runoff through the summer and fall. Across Canada, water availability, quality, and use vary temporally (from year to year and then season by season) and spatially (from province to province and from region to region within the provinces). The substantial seasonal and regional variability in the state and flow of water significantly influences agricultural activity within the Canadian setting.

The Panel maintains that on-farm water management has four objectives for which the hydrological cycle is manipulated through physical changes to the landscape (e.g., water diversion), technology (e.g., irrigation), or BMPs (e.g., snow trapping, reduced tillage practices, or enhanced drainage):

1. Promoting photosynthesis in agricultural plants during transpiration by maintaining soil moisture above the wilting point level in the root zone;
2. Facilitating seeding, tillage, and harvest by reducing excess soil moisture and ponded water on fields;
3. Providing on-farm surface water storage in ponds or lakes for livestock and irrigation; and
4. Managing the quantity and quality of discharges from agricultural land, including providing mechanisms for the disposal of operational by-products from agricultural activities (e.g., application of manure to farmland, disposal of liquid wastes in runoff, irrigation return flow, and cleaning of farm equipment).



Adapted from Stewart *et al.*, 2011

Figure 3.1

The Canadian Agriculture Hydrological Cycle

This figure illustrates the operation of the hydrological cycle in a conceptualized agricultural landscape. This cycle includes precipitation of snow and rain, storage and sublimation of snow, rapid snowmelt in the spring, infiltration of meltwater or rainfall into soils, storage and evaporation of water on the land, storage and evaporation of soil moisture, the flow of water in groundwater aquifers, and by overland flow and subsurface runoff to streams and lakes within the river basin.

The first objective (promoting photosynthesis) can be accomplished through irrigation, snow management, and tillage practices as well as selecting plants that have appropriate rooting and water use characteristics. The second objective (facilitating seeding, tillage, and harvest) can be accomplished by tile drainage, wetland drainage, and installation of culverts and channels in rural areas to improve drainage. The third objective (on-farm water storage) can be accomplished by management of local headwater streams, water supply canals, dugouts, tile drainage, snow management, groundwater pumping, and outflow damming. The fourth objective (managing discharges, including disposal of operational by-products) can be accomplished by, for example, tillage practices; land application of manure to enhance soil fertility; use of retention ponds and wetlands for runoff and/or agricultural waste where appropriate; discharge to a natural stream or shoreline; or development of irrigation return flow canals, drainage ditches, and tile and wetland drainage. Some of these manipulations enhance agricultural productivity and reduce the need for off-farm inputs, some compete with other human water uses (e.g., industrial and municipal uses), and some are harmful to the natural environment (e.g., co-location with water bodies, drainage ditches, and wetland drainage).

3.2 ISSUES IN WATER QUANTITY: WATER AVAILABILITY AND COMPETING USES

Water Availability for Agriculture

Water available for agriculture must provide for the four objectives of agricultural water management listed in Section 3.1. On-farm availability is governed by direct precipitation to agricultural fields, wind redistribution of snow, on-farm water storage, and losses of water through evaporation and sublimation. At larger scales, availability is determined by downstream concentration of runoff by river basins and movement of groundwater through the subsurface according to the hydrological cycle (AAFC, 2010a; Gray, 1970). There is also a strong seasonal component to availability, as agricultural water consumption is largely restricted to summer, whereas water supply is spread throughout the year. Thus water availability for agriculture depends on summer availability of soil moisture, surface water, and groundwater. Other constraints on availability can include factors such as allocation to competing uses, lack of information on surface water and groundwater resources, lack of information on water supply and demand, and poor water quality (AAFC, 2003c).

For the purposes of assessing water availability, the Panel observes that the most common indicators are soil moisture storage, surface water storage, groundwater storage, precipitation, evaporative demand, and streamflow, but their relative importance varies with the type of agriculture. For dryland agriculture, precipitation to the agricultural field, snow trapping potential, evaporative demand, and soil moisture status are important; for irrigation agriculture, knowledge of upstream rainfall and snowpacks, reservoir and groundwater storage, upstream water use, and streamflow are more important; for agricultural by-product processing, the distance to streams, field runoff frequency, and rate and streamflow discharge are of paramount importance. Moreover, the provision of water from surface water and groundwater sources, as well as the last two objectives of agricultural water management as stated above, requires that water availability and impacts be assessed cumulatively over the watershed and/or aquifer.

The potential for agricultural expansion can be affected by the availability and variability in water supply. As illustrated in Figure 3.2, several major regions of agricultural activity are already areas of high water stress. However, it is important to assess temporal variability and trends in water availability as well. Figure 3.3 shows the naturalized and actual flows of the South Saskatchewan River since 1912 as an example of the high levels of interannual variability and long term trends that are possible for blue water availability in agricultural regions. Naturalized flows have declined by 12 per cent since 1912 and actual flows are now 40 per cent less than the naturalized flows in the early 20th century. If the actual and naturalized flows may be assumed to be roughly equal in the early 20th century then of the 40 per cent decline in actual flows since that time, 70 per cent is due to upstream consumption and 30 per cent due to changing hydrology. It is not known to what degree climate and land use change in the mountain and foothills headwaters have influenced hydrology in the basin over the last century. The key message from this is that Canada does not have unlimited blue or green water available for agricultural expansion or intensification, and already has high threats to water availability in parts of interior British Columbia, the Prairie provinces, and southern Ontario, with significant water-based limitation to current agricultural productivity in some regions.

Water Demand by Agriculture and Other Sectors

As described in Chapter 2, while agriculture *uses* a relatively small amount of water compared with other sectors, it *consumes* the most of all sectors, which has important implications for water budgets and availability for competing uses (Beaulieu *et al.*, 2001; NRTEE, 2010a). Agricultural water consumption is typically defined as loss of water from the near-surface by evapotranspiration during photosynthesis of crops, direct evaporation of stored water, irrigated water, or water retained in a plant. However, evapotranspiration and evaporation return vast quantities of water to the atmosphere from agricultural lands. The Panel further notes that although some of the evaporated water forms precipitation in the river basin and may return as rainfall or runoff, most is lost from the regional water supply (Szeto *et al.*, 2008).

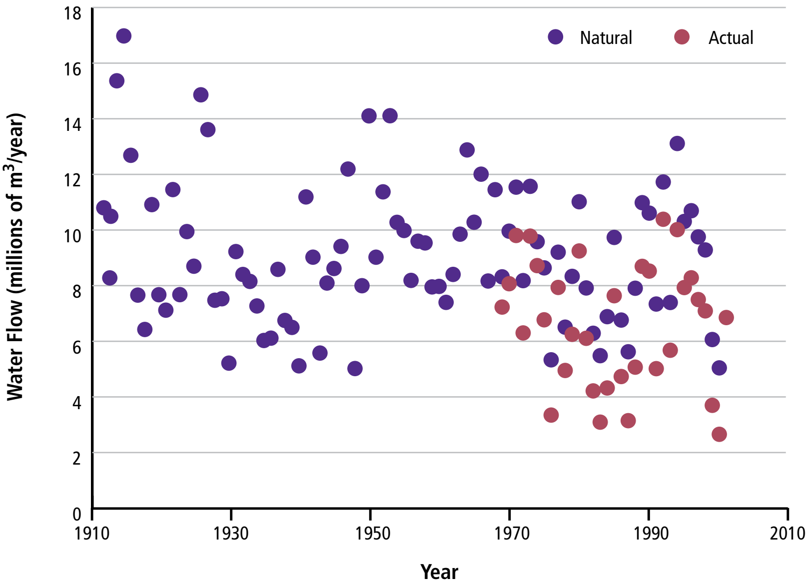
Data source: Environment Canada, 2011g

Figure 3.2

Threats to Water Availability by Sub-drainage Area in Canada, 2007

This figure illustrates the threat to water availability by sub-drainage area in Canada in 2007. There is a high threat to water availability in areas of south-western Manitoba, southern Saskatchewan, southern Alberta, and southern Ontario. There is also moderate to medium threat in the Okanagan Valley of British Columbia.

The vast majority (97.6 per cent) of Canada's harvested area is precipitation-fed and therefore does not use irrigation (AAFC, 2011c), and only 8.5 per cent of Canadian crop farms reported using irrigation in 2006 (AAFC, 2011c). However, of the water withdrawals made in agriculture, the majority (comprising about 83 per cent in 2005) is used for crop irrigation, with the bulk of the rest being used to support livestock production (Statistics Canada, 2010b). Surface water that is used for irrigation is primarily drawn from rivers, lakes or reservoirs, often at significant distances from the agricultural areas, whereas the groundwater sources are generally extracted from high capacity water wells in the immediate vicinity of the irrigated land. Water withdrawn for irrigation supports much higher evapotranspiration rates than would occur from dryland agriculture or natural vegetation; most withdrawals do not form return flow to the stream after irrigation, and so may be considered water consumption.



Data source: Calculations by John Pomeroy based on data from Alberta Environment

Figure 3.3

Naturalized and Actual Flows of the South Saskatchewan River Over the Last Century

This graph shows the naturalized (apportionment flows estimated by Alberta Environment) and actual flows of the South Saskatchewan River downstream of its confluence with the Red Deer River near the Alberta-Saskatchewan border. It demonstrates the high inter-annual variability of water flow through the southern Prairies, including low flows during the 1930s, 1980s, and early 2000s droughts, a gradual decline in water availability over time, and the growing difference between the flows that would have occurred without municipal, industrial, and agricultural withdrawals and actual flows.

Just under 530,000 hectares of Canadian cropland were under irrigation in 2010 (Statistics Canada, 2011b). Of this total, the vast majority was in the western half of the country. The largest estimated amount of water used for irrigation is in Alberta (59 per cent of the national total in 2010), followed by British Columbia (28 per cent), Saskatchewan (5.4 per cent), Manitoba (2.9 per cent), and Ontario (2.4 per cent). Other provinces use 2 per cent or less of the national total. In 2010, most irrigation water volume in Canada (52 per cent) went to field crops and tame forages (including barley and potatoes), followed by hay (31 per cent), fruit and vegetables (9.3 per cent), and pasture (7.3 per cent). Irrigation in the Prairie provinces is mostly used for field crops, hay, and pasture, while it is mainly used for fruit and vegetables in British Columbia and Ontario (Statistics Canada, 2011b). The water source for irrigation in Alberta, British Columbia, and Saskatchewan (over 90 per cent of Canadian irrigation) is in the high elevation mountains of Alberta and British Columbia where high precipitation in spring and summer, and storage of winter snow with peak melt rate in early summer, have historically assured stable, timely, and generally adequate irrigation water supplies. Warming of the Canadian Rockies and consequent decline in spring snowpacks may affect the timing, duration, and magnitude of streamflow from the mountains and so may require changes in water management and reassessment of the irrigation potential in downstream regions (Mote *et al.*, 2005; Stewart *et al.*, 2005). For instance, in the drought of 2001, voluntary reductions in irrigation were undertaken in Alberta due to low mountain spring runoff (Rood & Vandersteen, 2010).

In livestock production, water is primarily consumed by animals drinking, as well as for cleaning facilities, sanitizing equipment, and diluting manure (Corkal & Adkins, 2008; Kienholz *et al.*, 2000). Although raising livestock consumes much less water than does crop irrigation, it has significant implications for the natural environment, including greenhouse gas emissions, potential surface water and groundwater contamination, soil erosion, and air quality. In addition, livestock production requires a stable supply of high-quality water. Of note, while livestock water use is spread around the agricultural regions of the country, many of which have high water availability, irrigation is focused on regions of low water availability and therefore high water stress (de Loë, 2005).

Competing Uses

In all regions, agriculture's blue water consumption competes with other human uses of water such as municipal supply, industry, energy production, and the need to support important ecosystems, as well as recreational and cultural services. Withdrawals from the environment for industrial, municipal, and agricultural uses can affect both the quantity of water available and its quality. Each sector uses and consumes water differently, and their impacts on water quality are different (Corkal & Adkins, 2008; Environment Canada, 2004). For example, some large-scale projects such as hydropower dams can alter the entire watershed with potentially negative consequences (e.g., reduced streamflow for irrigation, lower levels of groundwater) or positive ones (e.g., increased availability of surface water and water storage for irrigation) (Prowse *et al.*, 2004).

It is also important to consider the cumulative impact on the quality of the water environment (another aspect of water use) of agricultural practices and municipal and industrial return flows, and other competing uses, particularly where intensive livestock operations, municipalities, and industry are close and where bodies of water receive their water from many sources (Environment Canada, 2004; UNESCO, 2012). For instance, there are currently surface water quality concerns associated with agriculture in the Lake Erie and Lake Winnipeg (Saskatchewan and Red Rivers) drainage basins (IJC, 2008; Tyrchniewicz & Tyrchniewicz, 2006;

U.S. EPA, 2010) and surface water quantity concerns along the Nicola River in British Columbia in 2009 led to limitations on the agricultural use of water to ensure that salmon had enough water to spawn (British Columbia Ministry of Environment, 2009). In addition, significant impacts on groundwater quality have been documented in agricultural regions near Abbotsford, B.C. (Wassenaar *et al.*, 2006) where groundwater is used extensively for municipal supply. Over the longer term, it is also important to understand how future changes in water supply, climate, and cropping practice may affect water usage and the agricultural industry.

Variations in Water Availability and Demand within Agricultural Regions

Water availability, quality, and use in Canada vary temporally and spatially. Changes in agricultural activities will affect the demand for water used in agriculture as well as the type of agriculture (crops versus livestock) and type of crop grown.[19] For irrigated agriculture and intensive livestock production, other activities (e.g., industrial, municipal, recreational, ecosystem needs) may be competing for the same available water. Climate change and weather variability will also influence the supply and demand of water. All the above factors are different for each region; therefore, water availability and demand also vary greatly among regions. British Columbia, for example, includes some of the wettest (coastal areas) and driest (parts of the interior) areas in Canada (Eilers *et al.*, 2010). In the late summer, even the wettest areas can have water shortages as most precipitation occurs in the winter (AAFC, 2003a). There is also heavy competition for water resources in certain areas of agricultural activity. Consequently, the province has experienced some conflict over water resources in these areas (AAFC, 2003a; de Loë & Moraru, 2004). In Ontario and Quebec, water for agriculture comes from a combination of surface water and groundwater sources (de Loë & Moraru, 2004), and certain parts of both provinces have experienced constraints on water supply from competing uses and issues with water quality related to agricultural production (AAFC, 2003a; de Loë & Moraru, 2004). On Prince Edward Island, groundwater supplies almost 100 per cent of the province's water (Martin *et al.*, 2000), and concerns have been raised about water quantity and quality (de Loë & Moraru, 2004). In the Prairie provinces, precipitation is limited for dryland agriculture and subject to high interannual variability. Irrigation demand is highest in Alberta, British Columbia, and Saskatchewan (Statistics Canada, 2011b), where surface water supplies that are derived upstream of the agricultural zone provide the source of irrigation water, and is relatively small elsewhere (Statistics Canada, 2011b), where local water supplies (including groundwater) are primarily used.

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[19] See Figure 2.2 for regional differences in the agricultural commodities produced across Canada.

Although there are always unique local agricultural water supply and demand issues that are specific to each province, overall the Panel observes that severe long-term droughts have affected agriculture most profoundly and frequently in central and western Canada, floods can affect agriculture nearly everywhere, and water quality concerns are prominent wherever there is intensive agriculture. Most Canadian agriculture must contend with some mixture of these three concerns.

3.3 ISSUES OF WATER QUALITY: NUTRIENTS, PESTICIDES, PATHOGENS, AND OTHER RISKS

The natural quality of surface water and groundwater resources is derived from the interactions of climate, vegetation, and hydrology with soils and geology, and thus exhibits wide variability in both space and time. Increasing pressures on the environment from urbanization, industry, and agriculture are leading to widespread degradation of water quality, although it is important to note that natural waters may depart from conventional perceptions of pristine water quality, due for example, to the characteristics of local soils (e.g., highly enriched in salts in the Prairies) or geology (e.g., impacts of natural oil sand deposits in the Athabasca river). Water contamination within the agricultural landscape is, however, an issue of major concern and results from a combination of point-source and non-point-source pollution. Point-source pollution refers to a specific, localized discharge of pollutants into a surface or underground water body (e.g., septic fields, farm yard runoff, fuel tank leakage, or manure pile leaching and runoff) (Bianchi & Harter, 2002). The most significant point-sources of contamination are likely to be located in the immediate vicinity of the farm yard, barns, and homestead and are normally associated with local, rather than regional, impacts on water quality. The primary influence is likely to be on the drinking water supply for the farm family and associated livestock and many recommended approaches to minimize these influences through BMPs are available.[20] However, most water pollution from agricultural practice occurs from non-point-sources (Kourakos *et al.*, 2012; Ongley, 1996), that is, the diffuse discharge of pollutants through the natural environment. Non-point-source contamination can occur over extensive areas due to the movement of air and/or water; water from rainfall, snowmelt, or irrigation moving over and through the ground can transport both natural and synthetic pollutants and result in their deposition in both surface water and groundwater receptors (Bianchi & Harter, 2002). Although agricultural stormwater discharges and return flows from irrigated agriculture may have a single point

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[20] See, for example, OMAFRA, http://www.omafra.gov.on.ca/english/environment/efp/efp.htm.

of discharge, they are conventionally considered non-point-sources of pollution in their transport of nutrients (phosphorus and nitrogen), metals, pathogens, sediments, and trace elements (Ongley, 1996).

The UN Food and Agriculture Organization (FAO) has identified some of the impacts of agricultural activity on both groundwater and surface water (Ongley, 1996) (Table 3.1). Poor water quality not only poses a health risk to people, animals, and ecosystems, it can also impact agriculture by degrading and thus reducing available irrigation source waters, reducing weight gain rates in affected livestock, and affecting food production (Corkal & Adkins, 2008). As a result, there is a growing need to evaluate the impacts of water quality on agriculture, not only the impacts of agriculture on water.

The environmental impact of water quality is frequently assessed based on end use. For example, Health Canada and Environment Canada suggest different recommended maximum acceptable concentrations of chemical and microbial constituents deemed safe for human consumption, animal consumption, and ecosystem health (CCME, n.d.). Within the agricultural environment, a unique suite of potential contaminants predominate; however, since a wide variety of end-users are present, the range of acceptable concentrations is also wide.

Table 3.1

Potential Impacts of Agricultural Activity on Surface Water and Groundwater Quality

Activity	Surface water impacts	Groundwater impacts
Tillage/ ploughing	Sediment transport of nutrients/pesticides; siltation of river beds resulting in loss of habitats.	Not applicable.
Fertilizing	Nutrient runoff leading to eutrophication; excess algae growth leading to deoxygenation.	Nitrate leaching to groundwater resulting in regional contamination.
Manure spreading	Spreading on frozen ground and during heavy runoff periods leads to high levels of contamination by pathogens, metals, phosphorus, and nitrogen.	Nitrate and pathogen contamination of groundwater at both local and regional scales.
Pesticide application	Biotic contamination; ecological dysfunction due to loss of top predators as a result of growth inhibition and reproductive failure; health risks from eating contaminated fish; long-range wind transport of pesticide residue as dust.	Leaching to groundwater impacting drinking water and irrigation water quality.

continued on next page

Activity	Surface water impacts	Groundwater impacts
Feedlots/ animal corrals	Pathogens (bacteria, viruses, etc.) leading to chronic public health risks; contamination by metals or veterinary medicines in urine and feces.	Potential leaching of nitrates, metals, veterinary medicines, and pathogens resulting in degradation of local water quality.
Manure storage facilities	Nutrient, pathogen, and veterinary medicine release to surface water through spills and overflows.	Nutrient, pathogen, and veterinary medicine release to surface water and groundwater through leakage and infiltration.
On-farm fuel storage	Local petrochemical contamination associated with spills and surface runoff from above-ground storage tanks.	Local petrochemical contamination associated with leaks from underground storage tanks.
Septic weeping beds	Not applicable.	Local leaching of nitrate, pathogens, metals and various human pharmaceuticals.
Barnyard runoff	Nutrient, pathogen and veterinary medicine release from animal exercise yards, barns, and silos through surface runoff.	Local leaching of barnyard runoff carrying nutrients, pathogens, and veterinary medicines.
Irrigation	Salt runoff leading to salinization; fertilizer/pesticide runoff leading to ecological damage; bioaccumulation in edible fish; high levels of trace elements (e.g., selenium).	Enrichment with salts and nutrients, compromising quality of both drinking and irrigation water.
Clear cutting	Land erosion leading to high turbidity in rivers and siltation of bottom habitat; increased runoff volume and flashier response to precipitation; potential loss of perennial streams.	Disruption of hydrological regime, often with decreased recharge.
Aquaculture	Release of pesticides and high levels of nutrients through feed and feces leading to eutrophication.	Not applicable.

(Adapted from Ongley, 1996)

In this review, the Panel considers water quality in terms of the contaminants commonly found in agricultural settings, including nitrogen and phosphorus, pesticides, and microbial indicator species routinely used to indicate the presence or absence of pathogens. Several emerging contaminants, such as agricultural pharmaceuticals, are considered as well, with the focus on the largest and most widespread non-point or diffuse sources of contamination. The Panel considered that within the scope of this report, the primary focus on issues related to water quality within the agricultural landscape would be on non-point or diffuse sources, because of the potential spatial extent of their impacts and the challenges for agricultural policy.

Nature of Water Quality Impacts

Nutrients

Although healthy soils contain nutrients essential for good plant growth, such as nitrogen, phosphorus, and potassium, supplementation is often necessary to maximize economic productivity (MacKay & Hewitt, 2010), and can result in risks to the environment and water quality. In some of the world's most advanced economies, nutrient pollution has been identified as one of the most important societal challenges. One of the potential consequences of excess nutrients in surface water systems is eutrophication, identified by UNESCO as one of the most important global water quality issues (UNESCO, 2009). Eutrophication refers to excessive plant growth in a water body that arises from nutrients being released into a nutrient limited water body. This affects aquatic ecosystems by subsequently reducing the dissolved oxygen content, potentially causing the extinction of other organisms (Environment Canada, 2010a). It also has impacts on recreation and water treatment for supply, and may be associated with toxins generated by blue-green algae which are harmful to humans and animals. This is therefore a critical issue for society, and one for which it is important to identify and manage the causes and effects.

The causes of eutrophication include air pollution, urban and rural domestic wastewater discharges, and the flushing of agricultural fertilizers and manures into receiving waters. The consequences can be extreme. For example, in 2007, Lake Winnipeg experienced an algal bloom reported to be 15,000 km^2 in extent, believed to have been the result of excess nutrients being received from multiple sources (Kling *et al.*, 2011). In 2011, Lake Erie experienced its largest algal bloom in the past several decades during an extremely wet period (NASA Earth Observatory, 2011). Many attribute the nutrient loading that produced this bloom to diffuse source runoff from agricultural lands draining into Lake Erie from both the U.S. and Canada. Under drought conditions in 2012 the bloom experienced in Lake Erie was only 10 per cent of the size of the one in 2011, showing the link between climate, runoff formation and nutrient delivery to lakes. While agriculture is often a major contributor, the relative role of agriculture in contributing to this pollution is often poorly understood, and there is also an important potential role for agriculture in mitigating some of these effects. In general, therefore, it can be seen that the interface between agriculture and water quality is complex and raises important policy issues related to measures for minimization of loads, mitigation of effects, and, more generally, the role of agriculture in providing environmental goods and services.

Agricultural intensification in Canada has greatly increased the risk of contamination of surface water and groundwater by nutrients. Evidence suggests, however, that the off-farm costs of mitigating soil and groundwater contamination by far exceed the costs of on-farm nutrient management practices (Lynch, 2009; MacRae *et al.*, 2007).

Nitrate

Though essential for crops and usually added in the form of inorganic fertilizer or manure, nitrogen can be harmful to people through consumption and can also contribute to degradation of ecosystem health (e.g., by promoting eutrophication) (Hatch *et al.*, 2002). The U.S. Environmental Protection Agency (EPA) recently noted that anthropogenic creation of reactive nitrogen [21] provides essential benefits for people (U.S. EPA, 2011). In fact, a large fraction of the population could not be sustained if synthetic nitrogen fertilizers did not significantly augment food production. However, most of the nitrate created by human activities is released to the environment, often with unintended negative consequences.

The EPA has pointed out that agriculture uses more reactive nitrogen and is responsible for more reactive nitrogen losses to the environment than any other economic sector (U.S. EPA, 2011). For example, in Chesapeake Bay direct additions of about 370,000 tonnes per year of reactive nitrogen by agriculture to the environment caused $1.7 billion in damages (U.S. EPA, 2011). Similar concerns exist in Europe. A 2011 European Nitrogen Assessment (Sutton *et al.*, 2011) estimated environmental damage related to reactive nitrogen effects from agriculture in the European Union at between €20 billion and €150 billion per year. This was compared with the benefit of nitrogen fertilizer to farmers, valued at between €10 billion and €100 billion per year. Clearly, the cumulative pressures on the environment are leading to hard questions concerning the present and future role of agriculture and farm-based economics. In the subsurface, the leaching of excess fertilizer nitrogen has resulted in extensive groundwater contamination in areas such as southern British Columbia (Wassenaar, *et al.*, 2006) and southern Ontario (Goss *et al.*, 1998). In fact, the U.S. National Academy of Engineering has identified management of nitrogen as one of the grand challenges facing that country (National Academy of Engineering, 2012).

Rates of nitrogen use in Canada vary by crop and geographical location; in 2000, these rates ranged from 25 to 225 kg/ha (FAO, 2007). From national modelling, Agriculture and Agri-Food Canada (AAFC) showed that the combined effect of

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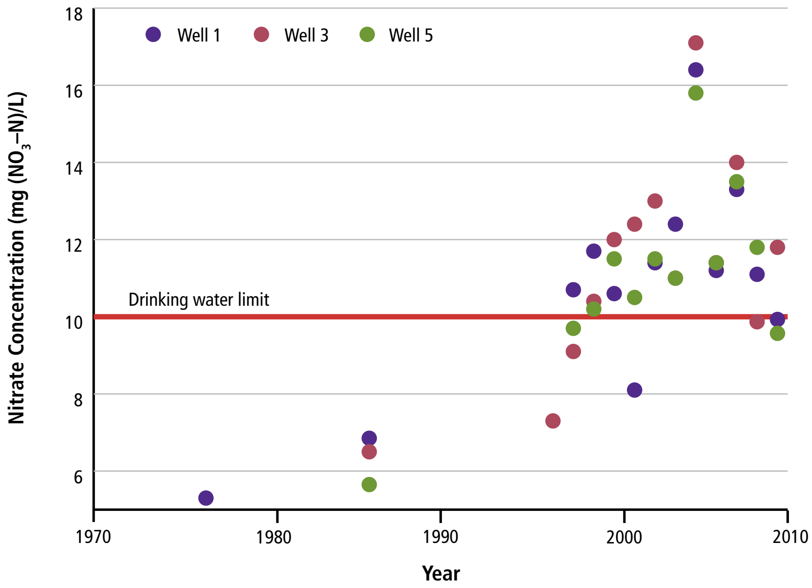
[21] Reactive nitrogen is all biologically, chemically, and radiatively active nitrogen in the atmosphere and biosphere of the Earth. It includes inorganic forms (i.e., ammonia, nitrogen oxide) and organic compounds (i.e., urea, proteins, and nucleic acids) (U.S. EPA, 2011).

fertilizers, manures, and nitrogen-fixing crops had approximately doubled residual soil nitrogen (the nitrogen content — measured as quantities of nitrate plus those of nitrite — of the upper soil after the end of the cropping season) between 1981 and 2006 (Drury *et al.*, 2010). AAFC estimated the risk of nitrogen loss to the aquatic environment based on these residual soil nitrogen levels. In 1981, 85 per cent of Canada's agricultural land was considered to be in the very low and low risk classes, with 10 per cent at high or very high risk. By 2006, the low and very low risk category had fallen to 66 per cent and the high or very high risk had increased to 17 per cent. While the overall pattern is of increasing risk, there are important regional differences. The Prairies tend to be at low risk; in 1981, Saskatchewan was entirely very low risk, though this had changed to 57 per cent in 2006 (Drury *et al.*, 2010). Ontario, Quebec, and the Maritime provinces are at higher risk. In 1981, 94 per cent of agricultural land in Prince Edward Island was considered at moderate risk, whereas by 2006, 100 per cent of the land was at very high risk. The Panel feels that the increasing risk of nitrogen loss from Canadian farms to the aquatic environment is a significant issue for agricultural water management that requires improved science to support implementation of improved management techniques.

The implications of this risk assessment can be seen in regional water quality across Canada. Where residual soil nitrogen values are high, nitrate loading of the shallow groundwater environment is also high. Nitrate concentrations in soil drainage waters captured from tile drains under corn grown in Nova Scotia exceeded drinking water limits 44 per cent of the time in the fall of 2008 (Smith & Kellman, 2011). In Prince Edward Island, leaching below the root zone from potato crops exceeded drinking water standards by about 50 per cent (Jiang *et al.*, 2011). Although the Prairies tend to be at low risk, applying manure to coarse soils can lead to very high concentrations of nitrate in shallow groundwater, with reported values in irrigated soils under conventional cereal silage production in Alberta averaging more than three times drinking water standards, with peak values more than nine times limit values (Olson *et al.*, 2009). These examples illustrate both the widespread occurrence of nitrogen loss to the environment beneath fertilized croplands and demonstrate the magnitude of the concentrations leaching past the root zone and moving in the shallow subsurface towards surface water features. This has important implications for drinking water treatment as well as ecosystem functionality.

Water quality analysis shows the impact of these elevated nitrate loadings on both regional and local groundwater resources. A regional survey of over 1,200 drinking water wells on Ontario farms found that about 15 per cent exceeded the drinking water limit of 10 mg/L NO_3-N (Goss *et al.*, 1998). In Abbotsford, British Columbia, extensive monitoring of groundwater quality from shallow and deep wells revealed widespread nitrate contamination, which was associated with historic agricultural land use management (Wassenaar *et al.*, 2006). Concentrations of nitrate in excess of the drinking water standards of 10 mg/L (Health Canada, 2010) have also been documented elsewhere in Canada including, for example, in the municipal water supply wells for the city of Woodstock, Ontario (Haslauer *et al.*, 2004) (see Figure 3.4). Clearly, the occurrence of elevated nitrate concentrations in groundwater within the agricultural environment is widespread and represents a significant threat to both private and municipal drinking water wells in Canada.



Data source: Haslauer *et al.*, 2004

Figure 3.4

Nitrate Concentrations in Municipal Water Wells of the City of Woodstock, Ontario

This figure shows how nitrate concentrations have progressively increased in municipal supply wells in Woodstock, Ontario, over 40 years, suggesting the legacy effects of earlier periods of nutrient loadings in the surrounding agricultural landscapes.

Whereas surface water systems show the effects of agricultural runoff relatively rapidly, groundwater systems tend to respond much more slowly with a significant time lag between the release of nitrate from the agricultural system and the ultimate impact on the groundwater. This has direct implications for the timing of any measures taken to reduce water quality degradation. Decadal time scales are not unrealistic (Jackson *et al.*, 2007; Jiang & Somers, 2009). Recent results presented by Lindsey and Rupert (2012) indicate that the occurrence of elevated nitrate concentrations in water wells has remained at similar levels or has in many cases increased in different areas across the United States over the last decade, as shown in a series of well water quality surveys. Legacy effects from over fertilization are still to be fully realized in the groundwater systems and the data suggest that nitrate concentrations may continue to increase for the foreseeable future.

Although these cases provide examples of groundwater quality degradation in Canada, data or information on the magnitude and extent of the impacts at the national scale are lacking. This gap will limit the development and targeting of effective strategies for sustainable management, including the implementation of appropriate BMPs (as discussed in Chapter 4).

Phosphorus

Phosphorus, which is yet another important nutrient for plant and animal growth, is also applied to soil through manure or mineral phosphate fertilizers (Leinweber *et al.*, 2002). However, additions of phosphorus to the land may lead to increased levels of phosphorus in soil over time and increased risk of its movement into water bodies. Due to low solubility and high sorption characteristics, phosphorous tends to present a higher risk to surface waters than to groundwater. In many, if not most freshwater aquatic systems, phosphorus is the critical nutrient for productivity. Hence, the movement of phosphorus into surface waters can result in eutrophication, as noted above. In addition, elevated levels of phosphorus have resulted in impacts to recreational water use, drinking water quality and treatment, and animal and human health (Leinweber *et al.*, 2002).

An Environment Canada (2011d) report on agriculturally-sourced nutrients noted a high level of public concern regarding phosphorus. Recent data suggested that as much as 32 per cent of surface water quality monitoring sites in the period 2005–2007 exceeded water quality guidelines for phosphorus more than half the time. As noted above, phosphorus is largely a surface water quality issue. It has been associated with severe algal blooms in Lake Winnipeg, Lake Simcoe, and other eastern Canadian lakes (Environment Canada, 2011d) and is of increasing concern in areas such as Lake Diefenbaker (Hecker *et al.*, 2012). The spatial patterns of phosphorus are highly variable across the different geographic regions of Canada, with concentrations in rivers typically increasing with distance downstream due to cumulative anthropogenic loads. The highest concentrations of phosphorus have been reported in the Prairies, upstream of Lake Winnipeg, and lowest concentrations in the headwaters of rivers in the Pacific drainage area and the upper Great Lakes region (Environment Canada, 2011d). The mobility and pathways of phosphorous transport within the agricultural landscape are complex and not well understood. A principle reason for this is that the monitoring network used to track the fate and transport of nutrients, including phosphorous, within the hydrologic cycle is sparse and insufficient to contextualize the many human and natural factors in play at specific sites. This makes it difficult to come to an adequate assessment of the problem or suggest what results improved agricultural management might provide (Environment Canada, 2011d). Additional details of monitoring requirements are contained in Section 3.5.

Rates of phosphorus use in Canada have increased over time (Chambers *et al.*, 2001). Rates of application depend on the crop and varied from 26 to 130 kg/ha in 2000, with potatoes requiring by far the highest level of fertilization (FAO, 2007). Elevated phosphorus levels have been documented in surface water within the South Tobacco Creek watershed in Manitoba (Li *et al.*, 2011). Levels of phosphorus in seven of eight Quebec rivers in livestock areas were recently found to be at least two times greater than the guideline for protection of rivers against eutrophication (Patoine *et al.*, 2012). AAFC noted that the phosphorus content of soils has been increasing since 1976 as intensification of agriculture has led to the application of phosphorus in excess of crop uptake (van Bochove *et al.*, 2010). This had led to very high concentrations of phosphorus in parts of British Columbia, Alberta, Ontario, Quebec, New Brunswick, and Nova Scotia. Using a risk assessment model, AAFC estimated that 98 per cent of Canada was at low or very low risk of phosphorus release to surface waters in 1981; by 2006, this had changed to 75 per cent at low or very low risk, 19 per cent at moderate risk, and 7 per cent at high or very high risk (van Bochove *et al.*, 2010). In eastern Canada, surface runoff combined with soil erosion by water are the most significant contributors to the risk of phosphorus contamination of surface water, while surface runoff is the primary contributing factor in western Canada (van Bochove *et al.*, 2010).

Pesticides

Pesticides — including fungicides, herbicides, insecticides, and bactericides — are widely used in both urban and rural environments to control weeds, insects, and diseases (Cessna *et al.*, 2010; Environment Canada, 2011b). Agriculture uses by far the largest amounts (Environment Canada, 2011b). AAFC reported that in 2006, over 35 million kilograms of pesticides were applied in Canada (Cessna *et al.*, 2010). The Prairie provinces together account for 84 per cent of pesticide use, with Saskatchewan alone accounting for almost half this total. However, pesticide use per hectare of cropland is greatest in New Brunswick and Prince Edward Island. The pesticides applied nationwide are herbicides (94 per cent), fungicides (4 per cent), and insecticides (2 per cent), but there is substantial variability in pesticide/fungicide use across Canada. Herbicide use, for example, represents over 80 per cent of total pesticide use in British Columbia, the Prairies, Ontario, and Quebec, while in many of the Maritime provinces, more than 50 per cent of pesticides used are fungicides (Cessna *et al.*, 2010).

Although pesticide use has had important benefits in increased crop yields, it may also contribute to environmental degradation. Environmental pathways include atmospheric transport as well as runoff and leaching of pesticides from agricultural land, potentially resulting in the contamination of surface water and groundwater sources (Cessna *et al.*, 2010). Pesticides have been detected in surface waters across all regions of Canada, and in between 2 and 40 per cent of water wells surveyed in British Columbia, Alberta, Saskatchewan, Ontario, Nova Scotia, and Prince Edward Island (Cessna *et al.*, 2010). Given the large applications of pesticides in the Prairies, it is not surprising that a 2012 study found multiple pesticides in all drinking water reservoirs tested (Glozier *et al.*, 2012). In addition, in an extensive survey of over 1200 farm drinking water wells in Ontario, Goss *et al.*, (1998) reported very limited detection of a common suite of pesticides. It is worth noting that due to improved pesticide efficiency and regulation, those currently in use tend to be more selective and less toxic than their predecessors and also have lower rates of application (Cessna *et al.*, 2010). The Food Systems 2002 program in Ontario has demonstrated that reductions in pesticide use do not have to come at the expense of productivity. Under the program, pesticide use declined by 38.5 per cent across the province between 1983 and 1998 while the average yield by hectare increased by 14.5 per cent over the same period (Gallivan *et al.*, 2001).

AAFC assessed the risk to water quality posed by farmland use of pesticides from 1981 to 2006. In 1981, 98 per cent of land was considered at low or very low risk, with the remaining 2 per cent at moderate to very high risk. By 2006, the area at low or very low risk was 86 per cent, with 13 per cent in the moderate to very high risk categories, the change being associated with increasing use of pesticides. Despite concern about the impacts of pesticides on human health and the environment, water quality guidelines have not been established for the majority of the pesticides used in Canadian agriculture (Cessna *et al.*, 2010). While data from across Canada show that, in general, the levels of detection fall below Canadian limit values *where they exist*, it is important to note that there is a high degree of variability in international standards. Canadian standards are in some cases less stringent than elsewhere. For example, the Canadian drinking water limit concentration for 2,4-D is 0.1 mg/L, whereas the standard used by the World Health Organization (WHO) and Australia is 0.03 mg/L and by Europe is 0.0001 mg/L (Australian Government, 2011a; EU, 1998; Health Canada, 2010;

WHO, 2011). In addition, there are no Canadian pesticide concentration guidelines for mixtures of chemicals, unlike the European Union's water quality guidelines (Cessna *et al.*, 2010).

Pathogens

Pathogens, microorganisms that cause infection or disease, can be viruses, protozoa, or bacteria and are often associated with animal and human feces. The main sources of water contamination by enteric pathogens include human sewage, deposition by animals and birds who have previously visited contaminated areas, and the leaching of manure from agricultural lands (Goss & Richards, 2008), the latter being the primary focus of this discussion.

Infectious, waterborne diseases are a major cause of morbidity. If ingested, several pathogen species such as *Giardia* and *Cryptosporidium* can result in immediate and acute gastrointestinal illness and thus are of considerable concern as a potential contaminant. For example, the outbreak in Walkerton, Ontario that led to seven deaths and over 2,000 serious cases of illness in 2000 resulted from the pathogens *E. coli* 057:H7 and *C. jenuni* being present in runoff from a livestock farm (O'Connor, 2002). The occurrence and source of most pathogens in the agricultural environment can be highly variable and complex in nature. For example, *Giardia* is often found in human, beaver, muskrat, and dog feces whereas *Cryptosporidium* is primarily associated with cattle manure (Health Canada, 2009a). Coliforms are "a broad class of bacteria found in the environment" that can originate from both human and animal sources (Boubetra *et al.*, 2011). Their presence in drinking water is often used to indicate the potential presence of other, more harmful pathogenic species due to their relative simple testing protocols.

While national monitoring of pathogens in Canada is not available, a 2012 study of four intensive agricultural watersheds across the country found waterborne pathogens in 80 per cent of the surface water samples collected (Edge *et al.*, 2012). Earlier provincial surveys also found microbial indicators in rural wells. In the Ontario rural well survey, for example, approximately 40 per cent of over 1,200 farm wells contained at least one of the target species, suggesting fairly widespread microbial contamination of shallow groundwater in agricultural regions (Goss *et al.*, 1998).

Research indicates that the rate, method, and timing of manure application and incorporation into the soil can significantly impact both the occurrence of pathogens in adjacent surface waters and nutrient loss (MacKay & Hewitt, 2010). The time of year when manure is applied also affects environmental performance;

winter spreading (often a result of manure production exceeding storage capacity) is regulated in many provinces as it carries a very large risk of odour, nuisance, and water contamination (MacKay & Hewitt, 2010). Outside the host organism, enteric pathogens lose viability with time. This provides the fundamental basis to effective control strategies, for example, for enteric infectious diseases from land application of urban wastewater sewage sludge using multi-barriers (e.g., using treatment, land use and planting, waiting, and harvesting restrictions) (Lang *et al.*, 2007; Nicholson *et al.*, 2005; Rogers & Smith, 2007).

The fate and occurrence of pathogenic species in groundwater is very poorly understood and an area of active research. Evidence suggests that the frequency and concentration of pathogens in surface water and groundwater correlates to hydrological events such as intense precipitation or snowmelt periods and to near-surface soil properties (Cey *et al.*, 2009). However, very little is known about the nature of these correlations or the event-based behaviour of waterborne pathogens. Considering the potential impact on human health, further research into microbes in surface water and groundwater within the agricultural environment is of high priority.

Veterinary Medicines

Veterinary medicines are used both to treat and prevent disease in animals, and livestock farmers commonly supplement animal feed with a range of pharmaceutical products. While the environmental effects of these products are an emerging area of science, international and Canadian studies have detected their presence in soils and water (see, for example, Lissemore *et al.*, 2006). A comprehensive 2003 review found that for most veterinary medicines, concentrations known to affect aquatic and terrestrial organisms are significantly higher than those observed in environmental concentrations (Boxall *et al.*, 2003). However, there are some examples in which measured concentrations are higher than those known to cause effects. Furthermore, there are few data to evaluate the effect of degradation by-products, and the data to determine whether more subtle long-term effects may arise are limited. Specific concerns include links between the use of antibacterial products and the development of antibacterial resistance, which can be transferred from animals to humans through environmental pathways, including soils and water. Studies have observed that the use of such chemicals leads to changes in microbial populations, including an increase in antibacterial-resistant bacteria in soils (Baran *et al.*, 2011; Boxall *et al.*, 2003). The occurrence and fate of this complex family of emerging contaminants are very poorly understood or documented and represent a priority area of research.

3.4 THE NEED TO INFORM WATER MANAGEMENT THROUGH INFORMATION ON WATER QUANTITY, USAGE, AND QUALITY

Patterns in demand for water by the agricultural sector vary over time. Demand could increase sharply in future, depending on future export markets and domestic crop decisions. Irrigation development doubled overall in Canada between 1950 and 2001, but the increase has not been continuous (NRTEE, 2010a). Some estimates suggest that an additional 3 million hectares of land could be developed for irrigation (NRTEE, 2010a), more than five times the nearly 530,000 total hectares that was irrigated in 2010 (Statistics Canada, 2011a). However, significant limitations to expansion exist. These include major infrastructure costs, uncertainty regarding access to suitable water sources, variable suitability of soils and topography, social reluctance to embrace irrigation in the farm community and negative environmental impacts from growth in irrigation on this scale (Corkal & Adkins, 2008).

If Canada helps fill the emerging demand for more meat products from developing economies, use of water by agriculture could also increase. Many farmers are interested in cultivating higher-value crops or livestock, including biofuel crops, all of which consume relatively more water (NRTEE, 2010a). The potential for achieving these shifts in livestock production and cropping patterns is a function of water availability and quality, climate conditions, and infrastructure constraints (Corkal & Adkins, 2008).

Increased consumption of water for agriculture makes water management more difficult and therefore requires more information to adequately manage water. There are already examples in Canada where water managers have had insufficient access to measurements and predictions of upstream inflows to reservoirs and hydraulic characteristics of rivers downstream of reservoirs. As a result, they have not been able to satisfy competing demands for water supply for agriculture and flood control (Centre for Hydrology, 2012). Satisfying competing demands for water supply and flood control becomes more difficult when annual inflows to reservoirs are reduced, but peak flows are not, as has happened on the South Saskatchewan River over the last 50 years. The Panel maintains that better information on surface water and groundwater quantity and usage is essential in informing the decisions of federal and provincial policy-makers, water managers, agricultural producers, and other stakeholders.

The quality of water resources is assessed using physical, chemical, or biological parameters and varies greatly due to natural processes and human impacts. Evaluating water quality across the agricultural regions of Canada is complex and challenging. Analysis of certain parameters can be costly and time consuming, land area is large and physically diverse, land use practices vary significantly from region to region, and the monitoring networks and sampling protocols are inconsistent across jurisdictions (CCA, 2009; CCME, 2006; Environment Canada, 2012c). In the view of the Panel, these are among the reasons why Canada's national data sets tend to be very limited in terms of both the spatial networks available and the temporal resolution of sampling. However, water quality monitoring is another essential input to effective decision-making, as government officials and other stakeholders need credible, accurate scientific information in order to determine optimal trade-offs, build consensus, and take effective action.

As fresh water is critical to the vast majority of economic activities — not just agriculture — understanding both the status and long-term trends in water quantity and quality is also critical to our future prosperity (Auditor General of Canada, 2010). Water quantity and quality need to be measured at suitable spatial and temporal scales to support sustainable water management in agriculture, both as a direct measurement to support decision making and as an input to predictive computer modelling of water quantity and quality at locations and times when it cannot be measured.

The Role of Water Monitoring and Evaluation

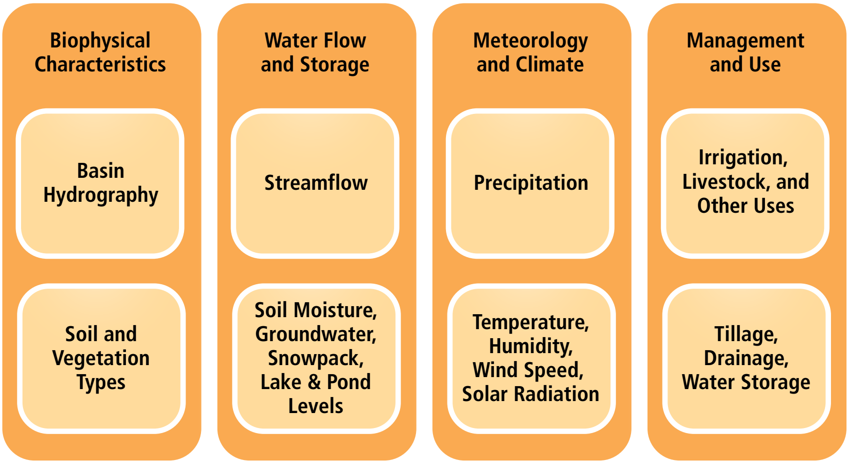
Environmental monitoring typically refers to a number of techniques used to sample water, air, soil, and other aspects of the natural world (Alberta Environmental Monitoring Panel, 2011). It is important to recognize that there are multiple reasons for monitoring, with different requirements in terms of the design of monitoring networks. The resulting data can be used to assess current environmental conditions, detect changes or trends over time, support operational management (e.g., for water resources management or flood forecasting), and/or estimate the potential impact of actions used to mitigate these conditions, (e.g., the effects of agricultural BMPs) (Alberta Environmental Monitoring Panel, 2011; CCME, 2011; Lovett *et al.*, 2007). Water monitoring is thus critical to (a) accurately assess the health of water resources across Canada, under pressure as they are from urban runoff and sewage, agriculture, industrial activities, population growth, economic development, climate change, and inequitable distribution (Auditor General of Canada, 2010); (b) support operational management of Canada's water resources; and (c) evaluate the effectiveness of management interventions. Information on water quantity and quality is also essential for the timely detection of emerging threats, while failure to do so could require more expensive remediation efforts

(Auditor General of Canada, 2010). In order for such threats to be identified, however, monitoring data across a range of spatial scales must be evaluated to determine cause-and-effect, and in general it is important to recognize that monitoring and evaluation form part of an iterative process — as new information becomes available, or new needs become apparent, monitoring networks require adaptation (Alberta Environmental Monitoring Panel, 2011). Such analyses must also be published and disseminated to promote understanding of existing conditions, trends, and potential risks to support effective policy development and environmental management (Alberta Environmental Monitoring Panel, 2011; Lovett *et al.*, 2007).

3.5 THE STATE OF WATER QUANTITY AND QUALITY MONITORING IN CANADA

Water Information for Agriculture

The Panel believes that access to adequate measurement and simulation information on water quantity and quality is particularly crucial for effective agricultural water management, which depends on the amounts and timing of natural precipitation (rain and snow) and, in the case of irrigation and other uses, may involve the manipulation of riverine flows and the storage of surface water and groundwater within watersheds. In addition, watershed simulation models require additional information to calculate streamflow, storage, and water quality. Consequently, this requires access to a wide spectrum of monitoring information regarding basic river basin biophysical characteristics, water and energy flows and storage, climate, meteorology, and water management, use and consumption (see Figure 3.5). Traditionally, such data have been based on ground observations, though optical and infrared satellite platforms have provided information on land use and evapotranspiration since about 1970. However, increasingly, satellite and aircraft-based remote sensing data are becoming available to support monitoring and modelling of water systems. Examples include the use of airborne light detection and ranging (LiDAR) measurements to provide high resolution digital elevation data (providing a transformational step forward for characterizing Prairie drainage basins), and satellite-based measurements of gravity changes (e.g., GRACE) from which water balances can be inferred. Microwave satellites are providing new information on near-surface soil moisture, snow water equivalent and land areas inundated by flooding. Snow measurements are discussed further in the context of the Saskatchewan River Basin example. There is great potential for expanded aircraft-borne remote sensing through the use of drones — the advantage is that drones can provide measurements under clouds and are less expensive to operate than airplanes.



Courtesy of John Pomeroy

Figure 3.5

Information Requirements for Agricultural Water Management in Canada

This figure shows the information requirements for agricultural water management in Canada. Note that these are but one set of information needs pertaining to water monitoring. Other information needs are highlighted in the schematic overview of the conceptual framework presented in Figure 2.1, and are discussed throughout the report.

Relevant river basin biophysical characteristics include the river basin drainage channel network, runoff-contributing area, depressional storage, topography, soil texture, and vegetation cover, including cropping and harvesting patterns. This information is used in watershed simulations to estimate water availability from ungauged basins for irrigation and livestock, soil moisture levels, evapotranspiration and irrigation demand, and drainage requirements.

Water flows in streams both upstream and downstream of the water management in question are also crucial, as is energy flow that impacts snowmelt, soil freezing and thawing, and evapotranspiration. Information on water storage as soil moisture, groundwater levels, lake/pond levels, snowpack water equivalent, and glacier mass is also used to calculate water availability and timing for irrigation, livestock, runoff potential, drainage requirements, tillage timing, and crop suitability. Precipitation intensity and duration (either as rainfall or snow), air temperature, humidity, wind speed, and solar radiation are significant both as current meteorology and long-term climate parameters in calculating water and snow availability and evapotranspiration in information to support planting and harvesting decisions. Information on severe weather events (tornadoes, hailstorms, extreme rainfall, blizzards, and droughts) is required to evaluate the need for emergency drainage or water storage to protect farmland and rural infrastructure, reservoir management, planting/harvesting decisions, and crop insurance. Finally, consumptive water use must be distinguished from total water withdrawals to determine total availability, and overall water quality must be known and assessed in terms of existing guidelines prior to agricultural use.

Surface Water Monitoring Programs in Canada

The responsibility for fresh water management in Canada is shared between the federal and provincial governments, as well as other stakeholders (see Chapter 6). Since its inception in the early 1970s, Environment Canada has been the federal agency responsible for the collection, interpretation, and dissemination of data and information on water (Environment Canada, 2012b). The government maintains two primary surface water monitoring programs: the National Hydrometric Program, focused on water quantity, and the Fresh Water Quality Monitoring program (Auditor General of Canada, 2010). A comprehensive review of these programs and the federal government's other water-related programs and policies was commissioned by Environment Canada in 1984, giving rise to what is commonly referred to as the Pearse Report and the subsequent adoption of a Federal Water Policy, intended to improve water management in Canada, in 1987 (Auditor General of Canada, 2010).

The National Hydrometric Program

The National Hydrometric Program, managed by the Meteorological Service of Canada's Weather and Environmental Monitoring Program, gathers, interprets, and distributes data and information on surface water quantity collected by 2,107 water and/or streamflow stations as well as data acquired by the private sector (Auditor General of Canada, 2010; Environment Canada, 2010e). The program involves shared responsibilities and costs among Environment Canada and other federal departments, provinces and territories, and the private sector (Auditor General of Canada, 2010). Information gathered through the program is used for purposes such as:

- planning, designing, and operating hydro-electric power generation, irrigation, and industrial infrastructure;
- research on aquatic ecosystems, climate change, and environmental impacts;
- water allocation and water-management decisions of water boards (such as the Prairie Provinces Water Board) and the International Joint Commission; and
- enforcement of regulations by various levels of government.

Monitoring information is disseminated through a national database; the program has also established national-level quality assurance procedures to validate its data, including the use of auditing to ensure that program officials and data-collection staff are following national practices. Environment Canada has established measureable performance objectives for water quantity monitoring information that have helped to set expectations for data quality and prompt dissemination through the National Hydrometric Program; however, there is a continued need for the definition and implementation of action plans for further improvement (Auditor General of Canada, 2010).

The Fresh Water Quality Monitoring Program

The Fresh Water Quality Monitoring program assesses and reports on the characteristics of Canada's surface water resources to help understand the impacts of human activities on water quality and the health of aquatic ecosystems. The program manages a total of 456 long-term water quality monitoring stations (Environment Canada, 2011e) (in addition to a number of shorter-term surveillance and biological monitoring stations) (Auditor General of Canada, 2010). These stations gather information for purposes such as:

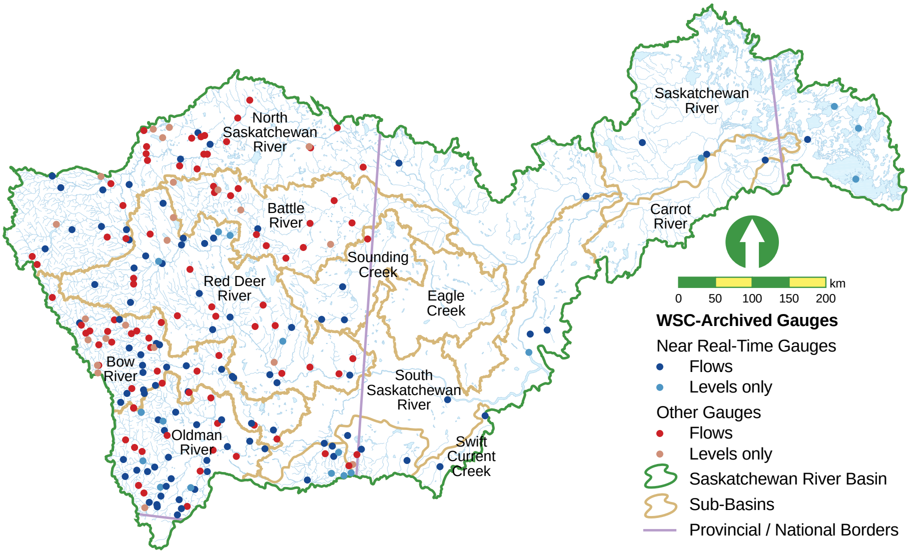
- determining baseline conditions of water quality;
- verifying compliance with established environmental guidelines and legislation;
- assessing responses to remedial measures;
- detecting emerging challenges and threats; and
- managing risks.

The Fresh Water Quality Monitoring program played a key role in developing the water quality indicator for the Canadian Environmental Sustainability Indicators (CESI) initiative (Auditor General of Canada, 2010). The federal government launched the CESI initiative in 2004 to establish a core set of environmental and sustainable development indicators. As explained in the Auditor General's report (2010), the water quality indicator is "intended to provide an overall measure of the ability of water bodies to support aquatic life at selected monitoring sites in Canada." The Fresh Water Quality Monitoring program contributes data towards this indicator, "together with 21 other water quality monitoring programs operated by various levels of governments and water boards" across the nation (Auditor General of Canada, 2010).

Unlike the National Hydrometric Program, the Fresh Water Quality Monitoring program has only four active federal/provincial arrangements. In addition, it has not established monitoring agreements with any of the territories, although it has a number of site-specific arrangements to monitor water quality (Auditor General of Canada, 2010). This lack of national consistent water quality monitoring arrangements impedes the ability to capitalize on the benefits associated with formal monitoring arrangements, including cost-sharing, the exchange of information and expertise, and the ability to compare reliable and accessible data from across the country (Auditor General of Canada, 2010; CCME, 2006). In addition, the Fresh Water Quality Monitoring program has no national database and lacks any uniform procedures to ensure that the quality of data from its regional databases is sufficient for its intended uses. Nor does the program "systematically track or communicate variances from water quality thresholds" across Canada (Auditor General of Canada, 2010). There is a critical need to establish a procedure to ensure the communication of discrepancies from water quality thresholds such that timely action can be taken to maintain or mitigate challenges in water quality and/or aquatic health (Auditor General of Canada, 2010). In addition to limited spatial sampling, a particular concern for water quality monitoring is that generally, the temporal frequency of the national network is monthly, at best. The Panel notes that for many contaminants, this is wholly unsatisfactory to capture both annual loads and extreme values. However, new technologies for continuous monitoring of water quality are now available (Estrin *et al.*, 2003; Pellerin *et al.*, 2009; Pellerin *et al.*, 2012), and offer the prospect of a cost effective solution to increased monitoring capability.

Monitoring in Practice: A Case Study of the Saskatchewan River Basin

The Saskatchewan River Basin (SRB), and in particular its southern tributary, the South Saskatchewan River, is home to the majority of Canadian irrigated agriculture and a large section of dryland agriculture, and has a climate that varies from sub-humid to semi-arid (Statistics Canada, 2011b). Under the South Saskatchewan River Basin water management plan adopted in 2006, the South Saskatchewan River has sub-basins under new water licence moratoriums due to perennial water shortages (Alberta Environment, 2006). The network of currently operating hydrometric stations that are part of the Canadian National Hydrometric Network for streamflow and lake-level measurement in the Saskatchewan River Basin is shown in Figure 3.6. Lake Diefenbaker supports over 40,000 hectares of irrigation (Government of Saskatchewan, 2008) and provides drinking water for many communities in the province (Government of Saskatchewan, 2008). The density of stations in the eastern section of the SRB is not high enough to estimate prairie inflows into Lake Diefenbaker, impairing effective management of the reservoir for both water supply and flood control (Centre for Hydrology, 2012). Prairie inflows are infrequent, but when they do occur they can raise reservoir levels above those anticipated from mountain runoff alone. Recent floods of agricultural land downstream of the lake have been attributed to the



Data source: Centre for Hydrology, 2012

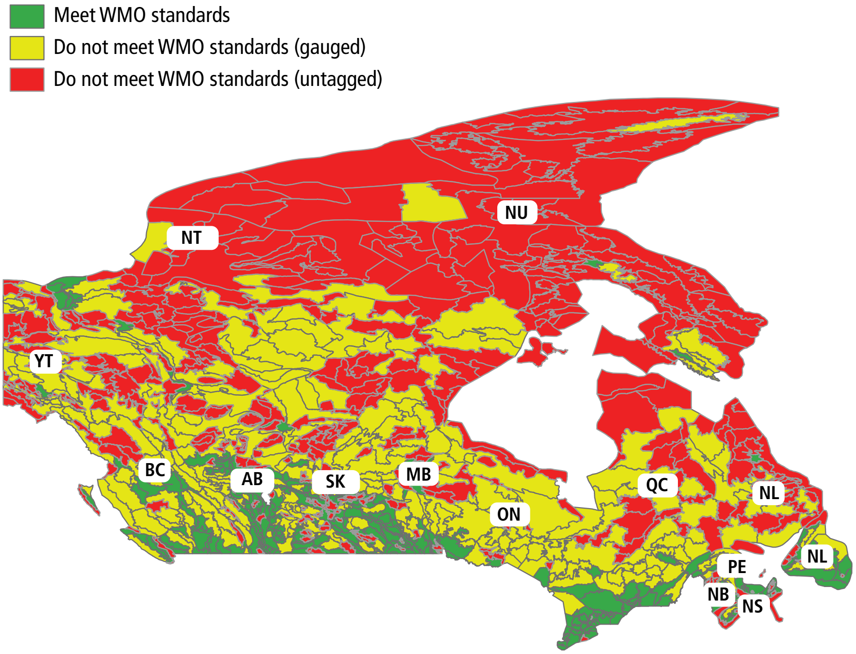
Figure 3.6

Hydrometric Stations in the Saskatchewan River Basin

This map shows the network of operating hydrometric stations that are part of the Canadian National Hydrometric Network for streamflow and lake-level measurement in the Saskatchewan River Basin. Gauges shown in blue provide near real-time flows using provisional rating curves via the Water Survey of Canada's website, while the red gauges provide data for the Water Survey of Canada (WSC) archive.

lack of measurements of prairie inflows, but maintaining low water levels in the lake in anticipation of such unmeasured inflows reduces its agricultural water supply function and irrigation potential in dry years (Centre for Hydrology, 2012).

In its most recent *Guide to Hydrological Practices* (WMO, 2008), the World Meteorological Organization (WMO) provided updated recommendations for minimum network densities based on physiographic units. According to a recent report that evaluated the Canadian National Hydrometric Network against these standards, 224,000 km^2 of the Prairie ecoregion met the WMO network gauge density standards, 157,000 km^2 did not; of the land area that fell below the standards, 28 per cent was ungauged and the rest gauged at network densities below WMO standards (Centre for Hydrology, 2012; Coulibaly & Samuel, 2011) (see Figure 3.7). This adds uncertainty to agricultural water management and reduces the opportunity to optimize agricultural production within available water supply.



Data source: Coulibaly & Samuel, 2011

Figure 3.7

Map of Canada Showing the Hydrometric Station Density Relative to World Meteorological Organization Standards by River Basin

This map shows a recent evaluation of the Canadian National Hydrometric Network against the World Meteorological Organization's minimum network densities, illustrating that several areas of Canada that do not meet these standards.

The alternative to direct measurement of streamflow is to use a hydrological model. Hydrological models use meteorological data to calculate streamflow and soil moisture, among other variables. The data, especially precipitation data, must be collected near to the main runoff generation zones, which in western Canada are mainly in the mountains. A soon-to-be published study found that the network of meteorological stations in the Canadian Rocky Mountains does not reflect the frequency distribution of elevations in this region (personal communication, John Pomeroy). Furthermore, each precipitation station in the Canadian Rocky Mountains samples on average an area of terrain 23 times larger area than that recommended by the WMO as its minimum standard. As mountain runoff is a primary water source for irrigation in western Canada, this gauge density is inadequate for agricultural water management. The Panel notes that this uncertainty can make management of water supply reservoirs for irrigation substantially more difficult, particularly when it is part of multi-objective operating regimes. Such uncertainty is considered unacceptable in the U.S., where the USDA operates the relatively dense SNOTEL network of high altitude snow and meteorology stations for the purposes of predicting agricultural irrigation water supply and irrigation reservoir management. Remote sensing and model products are potentially useful data sources to augment ground-based observation. Such data are available from the Meteorological Service of Canada (MSC) and the U.S. National Ocean and Atmospheric Administration's (NOAA) National Operational Hydrologic Remote Sensing Center (NOHRSC) in Minnesota to enhance this sparse data (Environment Canada, 2012a; NOAA, 2012b). Unfortunately, passive microwave remote sensing maps[22] of snow water equivalent (SWE) are unreliable during the melt period (particularly over unfrozen soils), where there are ice or dust layers, in regions with vegetation and for deep snowpacks (Centre for Hydrology, 2012). Consequently, the Panel observes that these maps require careful validation and bias adjustment from snow surveys to reliably contribute to streamflow forecasting.

The Canadian Meteorological Centre produces snow depth maps based on ground-based snow depth measurements interpolated over space and time using temperature and precipitation fields from the MSC numerical weather prediction model.[23] NOHRSC flies gamma airborne snow surveys over Missouri River and Souris River drainages but not over the Saskatchewan River basin. However, it does provide a one-kilometre resolution SWE product based on an assimilation of available surface and satellite information; this numerical weather prediction model outputs into a physical blowing snow and snowmelt model called SNODAS[24] that is partly based on snow models developed in Saskatchewan (Pomeroy & Li, 2000). SNODAS model results provided by NOHRSC extend northward into central Saskatchewan and Alberta and are used by flood forecasters in NOAA river forecast regions. SNODAS is considered state-of-the-art for operational SWE products, and it provides a potentially valuable information resource for river forecasting. If developed and implemented in the SSRB, the Panel believes this could prove to be a useful tool to assist in predicting and managing flood risks, an issue of growing concern in several areas of the Prairie provinces.

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[22] For maps, go to http://www.socc.ca/CMS%20FTP%20Data/snow/swe/snow_swe.html.

[23] For maps, go to http://www.weatheroffice.gc.ca/data/analysis/352_50.gif.

[24] For maps, go to http://www.nohrsc.noaa.gov/nsa/.

Groundwater Monitoring Programs in Canada

In comparison with the areal extent and historical record length of the surface water monitoring activities in Canada, groundwater monitoring is much more localized and frequently managed on a provincial level. Natural Resources Canada manages a National Groundwater Database that houses federal records associated with a limited network of groundwater monitoring wells and hydrogeologic data derived from federal projects and programs (see Table 3.2). Several provinces have established regional scale monitoring well networks over the last decade. For example, Ontario manages its Provincial Groundwater Monitoring Information System (PGMIS) as a web-driven network of over 400 monitoring wells that provides groundwater level and quality data across Ontario (Environment Canada & Ontario Ministry of the Environment, 2011). The information from the PGMIS provides an early warning system for changes in water levels caused by climatic conditions or human activities as well as changes in water quality from natural or anthropogenic causes. The information is being used to support informed decision-making on water-takings, drought management and land use planning. Similar monitoring well networks have been established in Alberta, New Brunswick and Prince Edward Island among others. Federal coordination of data management and integration from the provincial groundwater monitoring networks would be an essential step in developing the data base required to inform all aspects of the sustainable management of agricultural groundwater use.

Other Aspects of Water Monitoring

In addition to the surface water and groundwater monitoring programs described above, the federal government (through Environment Canada, Fisheries and Oceans Canada, Natural Resources Canada, Agriculture and Agri-Food Canada, and the Canadian Space Agency) is also responsible for collecting various types of atmospheric, climate, snowfall, and soil moisture data (Meteorological Service of Canada-Environment Canada, 2008). Some of these programs are listed and briefly described in Table 3.2. Provinces and municipalities are also involved in some additional aspects of water monitoring in their respective areas of responsibility.

Despite all of these initiatives and the substantial Canadian involvement in international monitoring activities, a 2008 report by the MSC found the national coordination between atmospheric, oceanic, and terrestrial monitoring programs to be insufficient (Meteorological Service of Canada-Environment Canada, 2008). As noted by the Canadian Auditor General's Office and others, such coordination is an essential characteristic for effective and efficient environmental monitoring systems (Auditor General of Canada, 2011; CCME, 2006).

Table 3.2
Examples of Water Monitoring Programs in Canada

Reference Climate Station (RCS) Network	A network of 305 stations managed by the Meteorological Service of Canada (MSC) that also includes the GSN (below). The RCS is primarily intended to determine climate trends on regional and national scales through a mixture of automated stations, human-based aviation weather observing sites, and climatological stations that measure daily temperature and precipitation.
Global Climate Observing System (GCOS) Surface Network (GSN)	Canada contributes 87 stations to the GCOS GSN, mostly automatic stations with standardized sensor suites; measurement, processing, and reporting algorithms; and inspection and maintenance standards and procedures. These stations, in addition to reporting on the Essential Climate Variables, measure atmospheric pressure, wind speed and direction, humidity, and snow depth. Some data gaps remain in the GSN, particularly in remote northern regions where installing and maintaining autostations is both expensive and prohibitive.
World Weather Watch/ Global Observing System (WWW/GOS) Surface Network	A synoptic network of 812 stations, including automated RCS that report on the suite of 13 Essential Climate Variables as well as, in some cases, solar radiation and soil temperature. Canada's hourly surface weather network includes these synoptic stations as well as aviation stations that produce Meteorological Aviation Reports (METARs). In addition, there are 149 Regional Basic Climatological Stations and 306 Regional Basic Synoptic Stations.
Glacier-Climate Observing System	Led by Natural Resources Canada's Geological Survey of Canada and based on *in situ* measurements of a reference network of glaciers in the Western and Northern Cordillera and Arctic Archipelago; documented changes in length and mass balance data from aircraft and satellite-based remote sensing are submitted to designated world data centres.
National Groundwater Database	There is no national network to monitor groundwater quantity and quality in Canada. There are relatively few active monitoring wells and the length of groundwater records is relatively short and often contains continuity breaks due to program changes. However, the National Groundwater database serves as a repository for the digital records of Natural Resources Canada and also catalogues information held by other agencies.
Provincial Groundwater Monitoring Networks	Several provinces have established networks of groundwater monitoring wells throughout their territorial boundaries to collect groundwater level and quality data on a spatial and temporal basis. These data are housed in provincially managed databases and are available for use by a variety of stakeholders. The design and size of the networks vary from province to province and the length of record is also province-specific.
Soil Moisture	There is no national *in situ* soil moisture monitoring network; rather, routine monitoring is ad hoc and lacks coordination between different agencies.

Source: Meteorological Service of Canada-Environment Canada, 2008

This table presents some of the Canadian monitoring programs and a brief description. This table is not meant to be comprehensive.

On a smaller scale, Canada does have some good watershed-level examples of well-coordinated, comprehensive monitoring strategies targeted towards specific areas of concern (see Box 3.1). The Panel believes that such examples illustrate how such an approach can contribute to informing the effective management of Canada's water resources.

Box 3.1
The Milk River Watershed: An Example of a Coordinated, Comprehensive Monitoring Strategy

Monitoring Strategy

The Milk River Watershed in southern Alberta (but also shared with Saskatchewan and Montana), is characterized by an arid climate, diverse flora and fauna, and is the only watershed in Alberta that drains south to the Gulf of Mexico (Milk River Watershed Council Canada, 2008, 2011d). The water of the Milk River comes from both snowmelt (50 to 80 per cent) and precipitation runoff (20 to 50 per cent), and is further augmented by an interbasin transfer from the St. Mary River system, which begins in the U.S. but flows into South Saskatchewan River Basin (Milk River Watershed Council Canada, 2011b).

The Milk River Watershed Council Canada (MRWCC)

A non-profit society, the MRWCC, was designated as a Watershed Planning and Advisory Council under Alberta's *Water for Life* strategy in 2003. It aims to encourage the sustainable use and integrated management of land and water resources by developing programs to assess and monitor the state of the watershed; increasing community knowledge and stakeholder involvement; and promoting BMPs to conserve wildlife and plant diversity (Milk River Watershed Council Canada, 2008).

Quantitative and Qualitative Monitoring Projects and Programs of the MRWCC

Since its inception, the MRWCC has initiated a number of water quality and quantity monitoring projects and programs to assist in guiding efforts in sustainable management. Some examples include:

- *Private Irrigators Pilot Project*, developed to accurately account for all irrigation water in the Alberta portion of the Milk River Watershed and enable a more comprehensive understanding of water use.

continued on next page

- *MiRTAP — Milk River Transboundary Aquifer Project*, launched in partnership with the Geological Survey of Canada, to create a standardized groundwater database that will allow for a unified three-dimensional model of the aquifer across all borders, providing for a better understanding of the current water groundwater supply and trends in water usage.
- *Water Quality Monitoring Program*, initiated in partnership with a number of other civic organizations, this project created a baseline for long-term surface water quality monitoring within the watershed.

(Milk River Watershed Council Canada, 2011c)

Outcomes: A Model to Build Upon in Other Watersheds

Ultimately, the preliminary outcomes of the projects initiated by the MRWCC between 2006 and 2008 illustrate the potential utility of real-time monitoring of water quantity and quality at the watershed level and the need for more comprehensive water resource information to assess and maintain the health of Canada's water resources moving forward. These projects are providing a wealth of information to help guide the development of an Integrated Water Management Plan, designed to foster an improved dialogue among government, non-government, and industry organizations, as well as landowners and residents, ultimately leading to more effective management of the watershed's natural resources (Milk River Watershed Council Canada, 2011a, 2011c).

The previous discussion has focussed primarily on data concerning the natural environment. For efficient management of water resources, information on water use is of critical importance. Commonly, water managers in Canada will have information on the amount of water licensed for use, but not the actual volumes and timing of water used. The Panel believes that further attention to data on water use is necessary to improve water management. A notable example of progress in this respect is the voluntary implementation of real-time monitoring of irrigation water use by individual farmers in the Milk River Alberta (see Box 3.1).

3.6 THE ROLE OF MODELLING, FORECASTING, AND ADAPTIVE MANAGEMENT

While data are essential to support the management of water for agriculture, in general the way in which data are used is through the application of computer models. These range from models used to estimate soil moisture from meteorological variables at the scale of an individual field for irrigation management, to models of whole water resource systems, used to optimize water allocations.

The Case for Predictive Water Modelling in Canada

It is accepted that not all streamflow, lake levels, groundwater and water quality parameters can be measured at the full range of scales. Therefore, water measurement must be supplemented by the modelling of water quantity and quality for ungauged basins and ungaugable situations (Sivapalan *et al.*, 2003). Such models typically consist of (a) statistical methods, which use historical data to calculate probabilities of flows, storage or water quality that can be extrapolated to ungauged basins; and (b) continuous watershed simulations that predict quantity and/or quality at various points in the watershed by conceptual or physically-based simulations of the hydrological cycle and associated biogeochemical fluxes (Spence *et al.*, 2005; Wagener *et al.*, 2004). Watershed simulations for ungauged basins can be based on parameters extrapolated from those determined by comparing water measurements to model outputs in gauged basins within the region (McIntyre *et al.*, 2005), by selecting parameters from measurements of watershed characteristics using remote sensing and field surveys (Fang *et al.*, 2010; Pomeroy *et al.*, 2007), or some combination of the two (Bulygina *et al.*, 2012; Dornes *et al.*, 2008).

Models also have a powerful role to play in the exploration of future conditions, which by definition cannot be measured. They can be used as a guide to planning and management, for example, by simulating the potential effects of different management strategies. Predictive watershed simulations are driven by meteorological data that are derived from station observations or atmospheric model outputs. When atmospheric model outputs are used, simulations can be run for possible future conditions such as climate change scenarios (Jackson *et al.*, 2007). A special case of model application is in forecasting, for which forecast weather conditions are used in real-time input to models to forecast estimates of flows, storage, water quality, and so on (e.g., Young, 2008b).

River Basin Modelling in Canada

Some provinces have water modelling capabilities for flood forecasting and water supply prediction purposes. For example, British Columbia, Ontario, Quebec, and Alberta have basin models (e.g., SSAR, UBC, WRMM, Hydrotel)[25] that are run continuously for a variety of purposes on a widespread basis over their river basins. Other provinces have geographical restrictions on model applications or no modelling capability. There is no coupling between provincial water models, nor are whole interprovincial river basins modelled by provincial governments. Environment Canada runs coupled hydrological-atmospheric models across provincial and national boundaries for water supply estimations on the Great Lakes basin and has demonstrated large scale modelling on the South Saskatchewan and Mackenzie River basins (Pietroniro *et al.*, 2007). These are not operational models for water management or flood forecasting purposes. There is no regular operational water quality modelling in Canada, though water temperature is modelled in some provinces. Alberta has a water management modelling capacity for basins impacted by irrigation water demand. Many universities have hydrological, water management, and water quality modelling capability.

Canadian meteorological forecasting is primarily performed by Environment Canada using the Geo-mapping for Energy and Minerals (GEM) numerical weather prediction model for periods up to three weeks and climate models for seasonal forecasts. UBC provides a GEM ensemble forecast product for BC Hydro's water management that is also used by Alberta Environment for forecasting. Water forecasting is performed in Canada by provincial environment and agriculture agencies for flood risk management and for water supply using a variety of methods.

Implications for Agricultural Water Management

Agriculture is concerned with all of the above methods in order to manage risk associated with agricultural production through on-farm management, and by water supply management through provincial authorities. Simulation models have an important role to play in the evaluation of the potential impacts of climate change, and in the evaluation of impacts of alternative management strategies (e.g., Jackson *et al.*, 2007). However, the complexities of cold region hydrology pose significant challenges for simulation models, for both hydrology and water quality. There is a particular need for improved modelling to represent the effects of agricultural management, including BMPs, at local and regional scales, and a general need to represent better the uncertainties in these simulations.

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[25] See, for example, Government of Alberta, 2005.

Where statistical methods based on historical climate, land use, water flow and storage are used to predict risk from extreme hydrometeorological events, the problem of hydrological non-stationarity causes substantial uncertainty as probabilities based on the historical record are not necessarily valid for future events (Milly *et al.*, 2008). Climate change is a primary source of hydrological non-stationarity. For example, changes in rainfall, snowfall, and streamflow over time have been detected in Canada (Burn *et al.*, 2010; Shook & Pomeroy, 2010, 2012; Dery *et al.*, 2009). In most cases, streamflow and peak streamflow are decreasing and spring and fall snowfall is shifting to rainfall. In the Prairie provinces, the length of rainfall events is increasing and one-day intensities are decreasing (Shook & Pomeroy, 2012), but in other regions the intensity of precipitation events is increasing (Mailhot *et al.*, 2010). Annual maximum rainfall events are shifting from summer to spring or fall (Mailhot *et al.*, 2010). This non-stationarity is resulting in a longer growing season but not necessarily greater water availability to support agricultural production over the growing season. The Panel believes this represents a significant risk to Canadian agriculture.

Both strong monitoring and strong modelling are needed to manage agricultural risk in a time of non-stationarity. The U.S. National Academy of Sciences (NAS) (2011) suggests:

> Although a full understanding of the hydroclimatology is yet to be secured, practical designs to cope with the possibility of elevated climate and hydrologic extremes based on historical time series and ad hoc margins of error are available for use and these techniques do rely on sufficient observational data. Basic monitoring of key elements of the hydrologic cycle provides an irreplaceable information resource that is particularly critical in a non-stationary environment.

Although the U.S. NAS report emphasizes the need for a strong observational network for meteorology and water, it warns that this should not replace advances in forecasting: "reliance on observations-based, *a posteriori* analysis — although practical in the short term — may obscure the inherent value of research aimed at causality and improved forecasting" (NAS, 2011).

Given that Canadian monitoring and forecasting capability does not appear to be as advanced as that in the U.S., the Panel believes that the development of an improved coupled monitoring and forecasting capability in Canada would provide for better risk management in agriculture, particularly in the light of unprecedented hydrometeorological non-stationarity due to climate change. For instance, hydrological forecasting for water supply and flooding is often done in different sections of provincial environment ministries and forecasting for soil moisture is done in federal and provincial agricultural ministries, while measurements are taken in a wide range federal and provincial government ministries. There is limited collaboration among these groups to optimize observation networks and prediction systems for agricultural water supply. The Panel believes that substantial benefits would accrue to Canadian agriculture by formal coordination of hydrometeorological observations networks and weather and water supply prediction systems for both dryland and irrigation agriculture.

Provision of improved estimates of probabilities of extreme hydrometeorological events and water supply can aid in adaptive management of agricultural activities and in the design of improved water management techniques for Canadian application. This will be particularly important as non-stationarity due to climate change causes significant uncertainties for global agriculture (Nelson *et al.*, 2010). Adaptive management will be needed for Canadian agriculture due to greater extremes of flood and drought under climate change and to changing hydrometeorological conditions of less snowfall and snowmelt runoff. Increasing inter-annual variations in hydrometeorological conditions will require that agricultural land managers and other stakeholders have a wide range of management techniques available to them that can be deployed with as little notice as possible (Pahl-Wostl, 2007; UNESCO, 2012). Expanded diversity of management on the farm may also be important in the resiliency of agricultural production in the face of high predictive uncertainty and hydrometeorological non-stationarity.

Foresight and Predictive Exercises to Forecast Water Availability

As discussed in Chapter 2, in the face of uncertain futures, new methods are needed for planning and risk management. Traditional methods of prediction have important limitations (Lempert & Schlesinger, 2000), and new approaches are needed for the management of risk under highly uncertain water futures (Wheater, 2009).

Foresight exercises are tools used to help investigate the state of water availability and consumption behaviour. One such foresight exercise was carried out in Canada by the National Round Table on the Economy and the Environment (NRTEE), an independent organization composed of "sustainability leaders" from business, academia, labour, community leaders, and so on, that advised the government of Canada on policy. In 2010 and 2011, the NRTEE published two reports, *Changing Currents* and *Charting a Course*. These reports describe the state of Canada's water resources and industry (including agriculture) and municipality water usage, and predict water usage (NRTEE, 2010a, 2011).

Organizations elsewhere have also undertaken foresight exercises related to future water use, this being of interest to governments worldwide. For example, in the United Kingdom, predictions are regularly carried out by the Foresight Programme, an agency headed by the government's Chief Scientific Advisor that reports directly to the Prime Minister and Cabinet. One of their 2011 reports, *The Future of Food and Farming*, predicts how pressures on the global food supply will shift as earth's population grows and discusses how agriculture can meet demand while maintaining the health of the environment (Foresight, 2011). While foresight exercises can be a useful tool, it must be noted that they are the opinions of one group of authors and the scientific basis behind any predictions must be critically examined.

An example of a predictive exercise focused on improved understanding of water flow is taking place in Australia, where access to sufficient fresh water is of particular concern. The Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia's national science agency, has established The Seasonal and Long-Term Water Forecasting and Prediction project (part of the Water Information Research and Development Alliance). The mandate of this agency is to accurately monitor, assess, and forecast the availability and condition of fresh water in Australia. They plan to have developed accurate statistical methods for seasonal forecasting of streamflow and runoff by 2013. They also have modelling approaches for streamflow forecasts (CSIRO, 2011). Although this agency does not predict how usage will change, the information from the predictive tools will be made available to other government departments for making water policy decisions.

Future Directions in Monitoring and Modelling

To ensure that Canada's fresh water resources are sustainably managed, it is necessary to assess all potential risks to water quantity and quality. The Auditor General of Canada has recommended a risk-based approach to establish water-monitoring priorities that would allow Canada to maximize existing resources by focusing on those activities and substances that are likely to pose the greatest risks to water quantity and quality (Auditor General of Canada, 2010). However, a risk-based approach based on historical observations alone will underestimate risks due to non-stationarity from climate change. Also, it is not physically possible and may not be economically desirable to monitor all possible risks. These factors dictate that an integrated approach to risk management is needed that combines monitoring, modelling and analysis, and addresses the associated uncertainties (see AEMP, 2011). This can best be achieved within a framework of adaptive management, as discussed above.

The Panel also feels that an integrated water and climate monitoring and forecasting capability in Canada would provide for better risk management in agriculture in light of unprecedented hydrometeorological non-stationarity due to climate change. The Panel maintains that such an approach could make substantial contributions to Canada's ability to sustainably manage its water resources, providing much needed input for mitigating risks, capitalizing on opportunities, and informing policy and management decisions.

Review of Key Findings

The State of Canada's Water Resources for Agriculture

- Access to good quality fresh water governs Canadian agriculture, but agriculture can also have important effects on the water environment. Understanding water quantity and quality and the linkages between land and water management is essential to managing water and hence to the success of the Canadian agriculture sector.

Issues in Water Availability

- For most agricultural land, water availability depends on natural precipitation, but irrigation and intensive livestock production represent the major consumptive uses of water in Canada and are in competition with other water users. Canada does not have unlimited water available for agricultural expansion or intensification, and already experiences high pressures on water availability in parts of interior British Columbia, the Prairie provinces, and southern Ontario, with significant water-based limitation to current agricultural productivity in some regions.

Issues in Water Quality

- Significant water quality issues arise due to agricultural activities. These include effects of inorganic fertilizers and manures, pesticides, pathogens and veterinary medicines.
- A major concern for surface waters is eutrophication, primarily due to nitrogen and phosphorus; the largest groundwater quality issue is contamination from nitrates. The causes of nutrient pollution of surface waters include air pollution, urban and rural wastewater discharges, and the flushing of agricultural fertilizers and manures into receiving waters; nitrate contamination of groundwater largely comes from leaching of fertilizers and manures applied to agricultural lands.

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- The increasing risk of nitrogen loss from Canadian farms to the aquatic environment is a significant issue for agricultural water management that calls for implementation of improved management techniques. For instance, the occurrence of elevated nitrate concentrations in groundwater within the agricultural environment is widespread and represents a significant threat to both private and municipal drinking water wells in Canada.
- Phosphorus has been associated with severe algal blooms in large lakes in the Prairie provinces and Ontario; though risk assessments show that roughly one quarter of Canada is at moderate or high risk for phosphorus contamination, it is insufficiently monitored to adequately assess the problem or how it can be better managed.
- Pathogens in agricultural water have contributed to human health emergencies and deaths in Canada in recent years. Considering the potential impact on human health, further research into microbes in surface water and groundwater within the agricultural environment is of high priority.
- It is important to consider the cumulative impact of agricultural practices, municipal and industrial return flows, and other competing uses, particularly where intensive livestock operations, municipalities, and industry are close and where bodies of water receive their water from many sources.
- As the pressures on water quantity and water quality increase across Canada, agriculture and other sectors will need to work towards managing water use and consumption more efficiently and sustainably. The interface between agriculture and water quality is complex and raises important science and policy issues related to measures for minimization of loads, mitigation of effects, and, more generally, the role of agriculture in providing environmental goods and services.

Monitoring and Modelling to Support Adaptive Management

- Current data on water quantity and quality are inadequate in many respects. Measurements at suitable spatial and temporal scales are needed to support sustainable water management in agriculture, both as a direct measurement to support decision making and as an input to predictive computer modelling of water quantity and quality at locations and times when it cannot be measured.
- Canada's climate is changing, but projections of the future are uncertain. Drought has severely impacted western and central Canada, and flooding has affected all regions in the last decade; however, there are concerns that drought and flood are expected to increase in a warmer climate. The warming of the Canadian Rockies and consequent decline in spring snowpacks may require changes in water management and reassessment of the irrigation potential in downstream regions.

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- Adaptive management of Canadian agriculture is necessary to address changing climate. More generally, in the face of population and economic growth and rapid environmental change, the management of water resources in Canada is facing unprecedented challenges, and new approaches will be required for robust decision-making in the face of high uncertainties. Integrated monitoring and forecasting of hydrometeorology and water supply for agriculture can provide critical information to support adaptive management and is currently not practised in Canada. Integrated water and climate monitoring and forecasting capability in Canada would provide for better risk management in agriculture, particularly in the light of unprecedented hydrometeorological non-stationarity due to climate change.

4

Land and Water Management: Beneficial Management Practices and Agricultural Sustainability

- Changing Land Use and Land Management
- Managing Soil Water: Irrigation and Drainage
- Beneficial Management Practices
- New Perspectives for Sustainable Agriculture for Canada — Conservation Agriculture and Ecosystem Services Approach

4 Land and Water Management: Beneficial Management Practices and Agricultural Sustainability

Overview

Agricultural land and water management can have quantifiable, harmful impacts on the environment in Canada; however, the occurrence and causes of these impacts are not well understood due to a paucity of relevant data and in-field research. Beneficial Management Practices (BMPs) designed to minimize these environmental impacts have the potential to play a valuable role in preserving the required quantity and quality of the water resources in agricultural settings. However, additional research on BMP performance is a critical requirement to quantify local and regional scale impacts. BMPs also provide the context for two related concepts that offer the potential of important benefits from a more diverse agricultural sector: conservation agriculture, which aims to create resilient, productive landscapes in the face of uncertain futures; and ecosystem services approach, which recognizes the value of non-markeble services, such as flood control, water quality, and ecological diversity. A broader perspective of the role of agriculture in providing a wider range of goods and services to society could provide significant benefits and opportunities for the agricultural industry.

Agriculture is a critical factor for human well-being (Raudsepp-Hearne *et al.*, 2010) and a provider of a broad set of beneficial ecological goods and services.[26] As outlined in Chapter 3, however, agricultural activity also can have harmful impacts on water quantity and water quality. The challenge for society is to identify and implement strategies to manage the production of agricultural products in a sustainable way. The Panel believes that meeting this challenge will require a focused emphasis on critical research needs in concert with the adoption of conservation agriculture and an ecosystem services approach to land and water management. Specifically, this will require additional science and knowledge in the area of managing land and water in agricultural landscapes, evaluation of BMPs, and understanding the complex interconnections among the multiple ecosystem services produced in agricultural landscapes.

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[26] Ecosystem goods and services are benefits that people receive from ecosystems (Bennett *et al.*, 2009). Goods include food, timber, fibres, etc.; services include pollination, flood control, carbon sequestration, etc.

Issues connected with water quality in agricultural landscapes illustrate the need for additional science and knowledge in these areas. Throughout human history, water has been a receptor for domestic and industrial wastes. Urban centres and major industrial plants typically discharge at well-defined locations, and hence are examples of point-source pollution. Point-sources are relatively easy to identify and point-source pollution is generally measurable. As a result, most developed countries have effective controls in place to regulate these discharges. However, other types of pollution occur over extensive areas; non-point-source (or diffuse) pollution can be due to atmospheric deposition of contaminants, such as acid rain, or to widespread land management practices (e.g., crop production), and involve complex, and often poorly understood, environmental pathways and interactions. Water quality is therefore a complicated story — one in which agriculture plays an important but often poorly understood part.

Examples presented earlier, such as Lake Winnipeg, clearly show that major environmental water problems, influenced by agricultural practices, do exist in this country. But to what extent do they manifest themselves across the heterogeneous agricultural landscape in Canada? To what extent can agriculture play a leading role in solving these problems and, more generally, in providing ecosystem goods and services for society at large? This chapter is structured to cover the main topics of on-farm water management related to agriculture. In light of rapidly changing demand, coupled with the emergence and adoption of alternative land management practices, the nature of agricultural land use is constantly evolving. To provide context, Section 4.1 describes the current trends in agricultural land management, in the context of the diversity of the agricultural sector across Canada, and their environmental consequences. Section 4.2 discusses the challenges associated with managing soil water in support of productive crop management (including irrigation and drainage), while Section 4.3 examines the current status of BMPs designed to minimize the environmental impacts of agriculture. Finally, Section 4.4 concludes with a discussion of the shift towards conservation agriculture and ecosystem services perspectives on agricultural land management.

4.1 CHANGING LAND USE AND LAND MANAGEMENT

The Changing Agricultural Landscape

Canada has about 160.2 million acres of total farm area (Statistics Canada, 2012). Although the total farmland area has declined from a high of 174 million acres in 1966 (Statistics Canada, 2012), the proportion used to grow crops progressively intensified up to 2006 (Huffman & Eilers, 2010). Between 1981 and 2006, over

5 million hectares were added to the area of cropped land.[27] Within this period, production levels of various crops fluctuated over time. Overall, however, the total production of many types of crops increased, including winter wheat, corn for grain, dry field peas, soybeans, and canola. Livestock herd sizes also increased substantially. For example, from 1981 to 2006, hog herds increased in size by over 50 per cent and poultry increased by more than 30 per cent (Huffman & Eilers, 2010).

The adoption of conservation and no-till practices across Canada has more than doubled over a 15-year period (1991-2006), which illustrates the farming community's willingness to adopt new management practices that demonstrate value (Huffman & Eilers, 2010). Market conditions, producer strategies, climate, and other factors also have resulted in changes to certain trends in intensification. Nevertheless, questions about the environmental impact of agricultural intensification remain.

The latest trends in agricultural land use across Canada are reflected in the Census of Agriculture, a national survey conducted by Statistics Canada every five years. The latest survey, for 2011, released in the summer of 2012, reveals the following trends that occurred between 2006 and 2011:

- total cropped land decreased by 1.6 per cent, falling to 87.4 million acres;
- cropped land continued to be the greatest component of agricultural land use, representing 54.6 per cent of the total farm area;
- summerfallow decreased by 40.5 per cent, declining to 5.2 million acres;
- total pasture, the second largest component of land use (at 31.2 per cent) decreased by 4.3 per cent, representing 50.0 million acres;
- woodland and wetlands areas decreased by 8.8 per cent, representing 12.1 million acres, while "other lands"[28] increased by 35.8 per cent (5.5 million acres); and
- total head of cattle decreased by 18.9 per cent (falling to 12.8 million head), total number of pigs decreased by 15.7 per cent (falling to 12.7 million head), and total number of laying hens and pullets increased by 2.4 per cent (rising to 38.6 million birds).

(Statistics Canada, 2012)

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[27] See, for example, Statistics Canada, *Table 001-0017 – Estimated areas, yield, production, average farm price and total farm value of principal field crops, in imperial units, annual*, CANSIM (database), http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=0010017&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid=.

[28] Some land in Manitoba, Saskatchewan, and Alberta was reported as "too wet to seed" as a result of flooding. This land was categorized in the "other land" category as opposed to cropland or summerfallow. As conditions improve, this land could shift back to its relevant category (Statistics Canada, 2012).

Agricultural intensification has been associated with important changes to the physical and nutrient status of agricultural soils (see Section 3.3). However, a longer-term perspective, over a timescale of many decades, would show that even more dramatic changes have occurred related to land use and land management in the agricultural regions of Canada; for example, changes associated with the conversion of prairies from natural pasture to arable agriculture. Important scientific questions concern, on the one hand, the impact of these changes on the quantity and quality of the water environment and, on the other hand, the potential for agricultural management to mitigate their adverse effects. These questions are discussed further below.

Cropping and Tillage Practices

Major changes have taken place in cropping patterns in recent years. For example, summerfallow (leaving the land idle during the growing season) was used traditionally on prairies. The aim was to conserve soil moisture and enhance nutrient availability for the subsequent year, with weed control using tillage or herbicides. Nationally, the amount of farmland under summerfallow decreased by 25.1 per cent between 2001 and 2006 (Statistics Canada, 2009) and by 40.5 per cent between 2006 and 2011, to 5.2 million acres (mostly located in the Prairies) (Statistics Canada, 2012). This is due to the adoption of management practices that make more efficient use of available moisture and allow for extended crop rotations or continuous cropping under precipitation-fed agriculture (Eilers & Huffman, 2005) and also to the economic need to keep arable land productive (Statistics Canada, 2009) in the increasingly competitive agricultural environment. The conversion of marginal land to permanent cover or pasture likely also contributed to this decrease (Eilers & Huffman, 2005).

In addition to the changes in summerfallow, the proportion of cropland devoted to cereal crops decreased all over the country between 1981 and 2006. This was partly due to a combination of low commodity prices and high input costs for wheat and barley leading to the production of lower-cost perennial forages (alfalfa, tame hay, etc.) (Statistics Canada, 2009). The diversification of cropping has also led to more cropland devoted to producing oilseeds, pulses, forages, and to a lesser extent, potatoes, vegetables, berries, and grapes (Huffman & Eilers, 2010), and transitioning of some cropland and summerfallow land to seeded pasture to meet livestock feed requirements (Statistics Canada, 2009). Such transitions are relevant here as both crop type and management can change the patterns of snow accumulation and infiltration and flow of water through the soil, modifying patterns of surface and subsurface flow and hence river flows and groundwater recharge (Harker *et al.*, 2004).

It is worth noting that market preferences also play an increasingly significant role in cropping practices. One example is in the Ontario apple industry, where production has changed from low-density (100 trees per acre) to high-density plantings (1,000 trees per acre). Furthermore, the planting to production cycle was reduced from ten to three years. These changes were implemented in response to consumer preferences for newer varieties and larger fruit. Although the industry did not historically use much water, these changes created a need to irrigate for supplemental moisture to foster accelerated growth and produce saleable fruit within this condensed time frame (O'Neill, 2011). This change in cropping practice is significantly increasing demand and consumption of water in the orchard areas.

Other important changes have taken place in land management. Tillage practices apply physical, chemical, or biological methods to optimize the soil environment for plant growth (see Opara-Nadi, 1993 for a review of definitions). Since 1991, tillage practices in Canada have been evaluated in the Census of Agriculture using six different variables. These include areas of cropland prepared for seeding using conventional, conservation, and no-till practices and areas of summerfallow where weed control is accomplished through tillage, chemical application and tillage, and chemicals only (Huffman & Eilers, 2010). In this context, *conventional tillage* refers to cropland that is prepared for seeding by turning over the top 15 to 20 centimetres of soil, burying plant residues, and exposing the soil before a secondary tillage process to break up soil aggregates and create a smooth, even seedbed. *Conservation tillage* breaks up the soil and kills weeds but does not turn over the soil, while *no-till* practices maintain all plant residues on the soil surface (Huffman & Eilers, 2010).

No-till practices were used on 56.4 per cent of the area prepared for seeding across the country in 2011, up from 46.4 per cent in 2006. No-till systems are widely used in the Prairies, "where large farm sizes and erosion-prone soils enhance the environmental and financial benefits of low-impact, one-pass seeding" (Statistics Canada, 2012). However, other areas are beginning to adopt the practice more widely. Quebec, for instance, doubled its no-till area to about half a million acres while the number of farms practising no-till increased to 69.0 per cent. Certain crops and soil characteristics still require usage of conventional tillage in some areas. Nevertheless, conventional tillage declined to 19.0 per cent of all land prepared for seeding in 2011, a decrease of 30.9 per cent since 2006 (Statistics Canada, 2012).

Tillage practices and the associated use (and timing) of heavy machinery influence water cycling on cultivated lands as they can affect soil structure and the accumulation of snow and hence runoff and groundwater recharge quantity and quality (Boardman, 1995; Boardman *et al.*, 1994; Bronstert *et al.*, 2002; Evrard *et al.*, 2007; Pomeroy *et al.*, 1993). For example, bare soil (i.e., with no residual vegetation) is less likely to retain snow and is more susceptible to wind and water erosion and soil degradation, leading to loss in fertility as well as changes to soil moisture, runoff processes, and transport of nutrients (Huffman & Coote, 2010). Conventional tillage practices, which incorporate the majority of crop residue into the soil, increase the risk of soil erosion, while conservation and no-till practices, although not suitable for all crops, allow for more crop residue on the soil surface and can thereby minimize erosion and surface runoff (Huffman & Coote, 2010). Standing stubble from grains and oilseeds left over the winter can be used to trap wind-blown snow; in the Prairies, this increases the potential snowmelt infiltration into soils up to four-fold from that provided by summerfallow fields from which most snow erodes (Pomeroy & Gray, 1995; Steppuhn, 1981). Minimum tillage, through development of soil macropores, facilitates infiltration into frozen soils and hence a substantial increase in snowmelt recharge of soil moisture where snow management is practised (Gray *et al.*, 2001). In fact, between 1991 and 2006, increased awareness of the benefits of soil conservation coupled with increased availability of no-till equipment led to a two-fold increase in the use of soil-conserving tillage practices (i.e., conservation and no-till processes) (Huffman & Eilers, 2010). The shift to no-till planting accounts, in part, for the transition away from summerfallowing land (Statistics Canada, 2009): the proportion of summerfallow maintained by tillage also decreased by 27 per cent during this time, while reduced tillage decreased by 7 per cent and no-till (chemical only) practices increased by 34 per cent (Huffman & Eilers, 2010).

Overall, cropping and tillage practices significantly influence water quantity and quality within the cultivated land and Canada is moving towards better practices. However, effects are complex, with site specific benefits and some drawbacks, which as yet are only partially understood, particularly at the scales of relevance to river and groundwater management. Hence, the Panel observes that there is a need for more study to understand and quantify the effects on water quantity and quality, for both surface water bodies and groundwater systems, of these evolving trends in agricultural land management practices. This increased understanding will be critical in developing alternative management practices that will enhance the sustainability of cropland agriculture (Elliott & Efetha, 1999; van der Kamp *et al.*, 2003).

Impacts of Agricultural Land Management on Flood Risk

The combination of land clearing, at times involving deforestation, and enhanced drainage activities, both of which are designed to support agricultural land use, have had significant impact on the nature and frequency of flood events worldwide (for example, see Mainville *et al.*, 2006). In addition, there are increasing concerns for the effects of intensification of agricultural land management on flood risk. While relevant international literature is limited, recent U.K. studies have shown that changing cropping patterns and increased use of heavy machinery are associated with degraded soil structure and changing runoff processes. The phrase "muddy floods" has been coined to describe enhanced surface runoff from arable fields (Boardman, 1995; Boardman *et al.*, 1994). In grazed upland landscapes, intensification has been associated with agricultural improvement of poorly drained soils and greatly increased stocking densities. Adverse effects include surface compaction, increased overland flow, and increased intensity of runoff from fields and small catchments. While in recent years implementation of more sustainable practices has led to rapid improvement in soil structure (Marshall *et al.*, 2009), an important question concerns the quantification of effects at local and regional scales. For the U.K., simulations showed that these changes in agricultural practice could have large effects on flood runoff from fields and small catchments for small flood events (Ballard *et al.*, 2011; Bulygina *et al.*, 2009, 2011; Wheater & Evans, 2009). However, in large watersheds and for the large events important for flood risk management, the effects were modest (changes in peak flow of five per cent or less). It seems likely that this result may be applicable across a range of environments, but research is needed to support this statement. It is also worth noting that while potential large-scale impacts on flood risk from major events are rather small, the conservation measures used clearly have multiple benefits, including reduced erosion and sedimentation, improved water quality, and habitat conservation.

In Canada, chronic and acute flood risk is exemplified by the extensive flooding in the Prairies in 2011. However, the extent to which agricultural drainage has affected flood risk is an open question. Recent results from one study of a catchment, Smith Creek, Saskatchewan, suggest that for extreme floods, peak flows may not have increased, whereas the flood volumes transmitted downstream undoubtedly have (Pomeroy *et al.*, 2010). However, it is unwise to generalize from a single case study, and the Panel concluded that although the consequences of flooding and the basic connection between agricultural land management practices and flood risk are acknowledged and indeed observed, detailed understanding of the processes and conditions controlling flood characteristics in Canada is limited and the data required for flood risk assessment are weak.

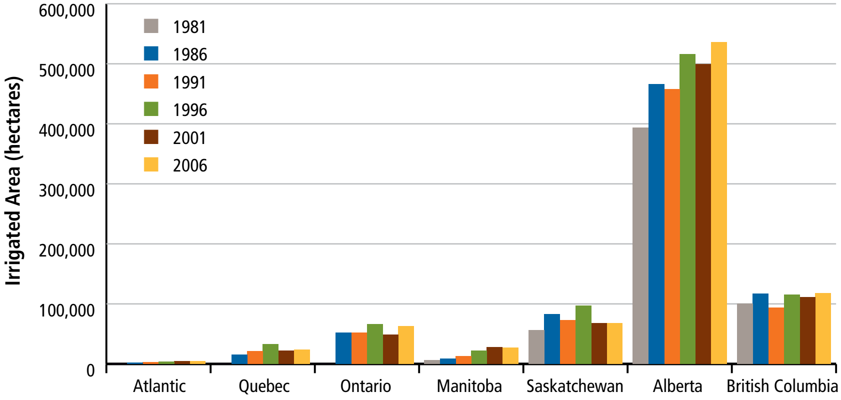
More generally, in most agricultural settings across Canada the replacement of native vegetation with seasonal, harvested crops has resulted in a redistributed snowpack, reduced vegetative cover overall, and exposed soils. In addition, enhanced drainage has provided conditions that accelerate transmission of surface water and shallow groundwater to drainage channel networks. These conditions have led to more extensive and higher peak surface runoff events resulting in increased downstream flood damage, channel erosion, and turbidity, as well as degraded water quality globally (Faulkner, 2010).

Flood risk assessment and management has become an issue of major concern across Canada. In 2011 alone, the cost of flood damage and disruption in Manitoba as a result of the spring flood exceeded $800 million (Province of Manitoba, 2011). This is likely to worsen as the impacts of climate change continue to be felt. There are areas of research related to tillage practices, crop cover, riparian buffer strips, and alternate surface drainage strategies that may lead to solutions that will help to reduce impacts of agricultural practices on flood characteristics and protect agricultural land from flood impacts (Wheater *et al.*, 2008). There may also be a role for agricultural land to provide floodplain storage in extreme events. In addition, new modelling tools and an improved understanding of the data required to support the predictive design of sustainable agricultural water management practices are emerging (Wheater & Evans, 2009). There is a need to establish pilot subwatershed study sites where these problems can be investigated in natural settings and at an integrated scale. The Panel concludes that additional research and data availability in these areas in support of the development of more effective flood risk management will be critical in the development of comprehensive strategies for sustainably managing water in the agricultural landscape.

4.2 MANAGING SOIL WATER: IRRIGATION AND DRAINAGE

Agricultural production globally has been significantly enhanced through the engineered management of water in the surface and near-surface environments. Irrigation and drainage practices are designed to control the amount and timing of soil moisture to optimize crop production and quality and to enhance on-field agricultural operations. Irrigation has been essential for the development of agriculture in areas of inadequate or marginal precipitation, but it is also used to enhance crop yield and quality. It often requires investment in drainage to control water table rise and salinization. Drainage is also needed to control soil water in areas with wet climates and/or “heavy” soils subject to waterlogging.

As irrigation practices represent the largest managed consumptive use of water in most areas of the world, in general they significantly influence and are fully dependent on water availability on a regional scale (UNESCO, 2012). For example, 70 per cent of the world’s water withdrawals from rivers, lakes, and groundwater are used for irrigated agriculture (UNESCO, 2012), equivalent to 80–90 per cent of consumptive uses (Foley *et al.*, 2011). In Canada, the intensity of irrigation works is geographically dependent but has increased overall between 1981 and 2006 (Poirier, 2009) (see Figure 4.1).



Data source: Poirier, 2009

Figure 4.1

Changes in Irrigated Hectares, 1981–2006

This figure illustrates the geographic differences in irrigated areas by province. Note that while irrigation levels vary by region and year, there was an overall increase between 1981 and 2006. Although total irrigated acreage in Canada has declined since 2006, the level of irrigation still exceeds 1981 levels and may increase again in the future.

Land drainage is extensive in many parts of Canada and continues to increase (Brunet & Westbrook, 2012). Enhanced drainage improves soil conditions for crop growth, improves access to land for agricultural machinery, and increases areas of agriculturally productive land. However, much of the expansion of drainage has been at the expense of wetlands, with associated loss of habitat and changes to water pathways, potentially affecting flood runoff, drought resilience, and water quality.

The management of soil water through irrigation and drainage has been shown to influence water availability for other anthropogenic and ecologic uses, and to have a major impact on surface water and groundwater quality (Rozemeijer *et al.*, 2010). At the same time, agriculture globally is facing pressure to increase production rates of existing arable lands (Foley, 2011). Hence, there has been a considerable interest in an expanded role for irrigation in the drier regions and enhanced drainage in wetter regions, both of which are anticipated to expand as a result of changing climate conditions across Canadian landscape. However, we currently understand little about the cumulative impacts of irrigation and drainage on the regional water environment. Furthermore, in addition to issues of water quantity and quality, the social, economic, and policy factors that may restrict the future development of these practices are also poorly understood in Canada, representing a significant threat to growth in many components of the Canadian agriculture industry. The major water quantity and quality issues associated with irrigation and drainage practices influencing the sustainability of Canadian agriculture, and associated science needs, are discussed in the subsequent sections. Socio-economic issues are discussed in Chapter 6.

Impacts of Irrigation on Water Quantity

An important aspect of irrigated agriculture is that it is normally developed in drier areas where competition for limited water resources can be intense. Irrigation water withdrawn from aquifers, lakes, and rivers could be available for other uses. This is not generally the case for agriculture based on natural precipitation. In addition, by their nature, irrigation systems frequently redistribute large volumes of water within the different components of the regional water cycle, which can affect other local water uses. Most irrigation water is "consumed" as crop evapotranspiration;[29] a residual amount may discharge to local surface waters as return flow through drains or surface ditching or infiltrate past the rooting zone to recharge groundwater systems. A final component of the irrigated water is consumed when incorporated into agricultural products that are removed from the land.

Water withdrawn for irrigation from natural water courses such as rivers and streams often competes with and may restrict other human uses — including, for example, industry, hydropower, and urban uses (which may include effluent dilution). In addition, irrigation withdrawals can influence flow rates to the degree that ecological health of the water course is impacted (Faurès *et al.*, 2007). Exacerbating this effect is the fact that, for precipitation-fed rivers, the peak irrigation demand normally occurs during the driest months of the year when stream discharge is at its lowest and the aquatic habitat is most vulnerable to water level fluctuations. The result of this is a potential restriction on access to source water when it is most required for irrigation. This may not be the case for rivers fed by mountain snowmelt, which tend to peak in early summer and sustain high flows into mid-summer, or those with flow regimes modified by dams or reservoirs.

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[29] While evapotranspiration returns moisture to the atmosphere, and hence some potential for recycling as precipitation within a river basin exists, most is lost from the regional water supply. Of the remaining water, the amount returned will depend on factors such as basin size, prevailing winds, and so on (Szeto, 2008).

Where groundwater resources are used for irrigation, several unique considerations arise that influence the sustainability of irrigation practices relative to water quantity. As irrigation periods tend to be relatively short in duration with high peak volume demands, large capacity wells are used. Intensive pumping from these wells can result in the depression of groundwater levels such that local surface bodies are acutely impacted. These impacts include reduction in groundwater-fed base flow levels in streams and rivers and lowering of water levels in wetland areas. A key point is that we do not understand the relationships between transient groundwater withdrawals and the influence on surface water features sufficiently to be able to make appropriate management decisions (CCA, 2009). In addition, the high volume groundwater withdrawals from irrigation wells may influence available groundwater resources for other users in the vicinity. A major complicating factor in assessing the sustainability of groundwater irrigation sources is the scarcity of data regarding extraction volumes. This represents a major data gap that must be addressed in order to evaluate the impacts of groundwater extraction for irrigation purposes.

The South Saskatchewan River case provides a powerful illustration of the fact that while irrigation expansion in Canada may be highly desirable to improve agricultural productivity and protect against current and future climate variability, it cannot be considered in isolation from a set of competing pressures for alternative water uses, including the needs for effluent dilution and environmental flows. Some 82 per cent of water consumption from the South Saskatchewan River is for irrigation, mainly in southern Alberta (Martz *et al.*, 2007). As a result, some sub-basins of the South Saskatchewan in Alberta are fully licensed (meaning that no new applications for additional water allocations are accepted, except for certain purposes such as for First Nations, water conservation, or improving aquatic ecosystems) (Alberta Environment, 2006). This has led by necessity to improved efficiencies of water management and also to water trading within irrigation districts. However, it raises challenges for future economic development and for environmental flows. In-stream flow *objectives* have been specified for water resources management, but these fall well below the perceived in-stream flow *needs* (Poirier & de Loë, 2011).

The breadth of potential impacts of climate change on water within agricultural systems continues to be intensely debated. Recent observations associated with conditions of climate variability in many areas across Canada and elsewhere have provided some insight into the nature of these potential impacts. Specifically relevant to irrigation are the expected increases in magnitude and frequency of drought conditions and the reduction in snowpack, which replenishes both the soil moisture and groundwater storage during spring melt and produces the dominant component of streamflow in the Rocky Mountains. As a result of these changing climate conditions, demand for irrigation water is likely to increase at the times when critical environmental flows are at their lowest, placing ecological health at further risk. For areas dependent on snowmelt runoff, there are concerns that a warming climate is changing magnitude and timing of snowmelt, with implications for timing of water availability for irrigation (Nazemi *et al.*, 2012). Global climate models suggest that warmer conditions are likely to prevail in Saskatchewan and Alberta, provinces with high intensity of irrigated land in Canada. The nature of potential changes to precipitation is uncertain, although increased variability is expected (Kundzewicz *et al.*, 2007; Mearns *et al.*, 2012). Either way, these changes will increase pressure on the agricultural industry to expand irrigation practices to maintain viable production (Turral *et al.*, 2011). Thus, the potential influence of climate change on demand for irrigation and drainage remains a major research question and one that must be considered of utmost priority. Reinforcing the concerns raised in Chapter 2, both the challenges and opportunities for agriculture that will result from climate change cannot be identified and evaluated properly without monitoring data, and the capacity to use those data.

Impacts of Irrigation on Water Quality

Water quality aspects of irrigation fall into two main categories: the impact of water quality on irrigation; and the impact of irrigation on water quality. With respect to the former, the food industry, an important driver for monitoring and managing source water quality, is increasingly interested in certifying agricultural products (see Box 2.3), including the quality of irrigation water. The Panel also noted that, in some areas (e.g., southern Alberta), increasing pressures from urban runoff are adversely affecting irrigation water quality (WID, 2011). The combination of these factors will place increasing requirements for data on irrigation water quality, something that may become critical for Canadian agriculture to maintain market competitiveness as the demands for environmental certification expand.

Considering the impact of irrigation on water quality, two sets of problems typically arise. First, irrigation commonly involves a return flow to surface water receptors through enhanced drainage. As a result of fertilizer and pesticide use on croplands, the return flows can accelerate the transfer of these potential contaminants from the agricultural fields to surface water and groundwater systems, resulting in degraded water quality. For example, a study of manure applications in irrigated soils in Alberta showed very high nitrate concentrations in shallow groundwater (with peak concentrations approaching 10 times that of drinking water limits) (Olson *et al.*, 2009), which may discharge into adjacent surface water courses as baseflow or through tile drainage systems. A major implication is that the receiving waters may subsequently become unusable by downstream irrigation systems due to elevated levels of various contaminants.

Second, long-term irrigation in various parts of the world has been associated with the degradation of surface water and groundwater quality in the vicinity of the irrigated lands and downstream, most notably where near-surface water tables have led to soil salinization (Dehaan & Taylor, 2002; Khan *et al.*, 2006). The magnitude of the impact, which can be seen to various degrees throughout the world, tends to progress slowly (Khan *et al.*, 2006).

In Canada, over one million hectares of surface soils within the Prairie provinces of Manitoba, Saskatchewan, and Alberta are rated at moderate to high risk of severe soil salinity (Wiebe *et al.*, 2006). Irrigation may enhance the flushing of natural minerals from the shallow subsurface to the groundwater system, leading to increasing concentrations of salts near the water table. This can lead to an increase in soil salinity through two mechanisms. Beneath most irrigated lands, water tables have been documented to rise as a result of the elevated rates of groundwater recharge associated with infiltration. Salts that have accumulated beneath the root zone are redissolved into the rising groundwater. These salts combine with those flushed by the irrigation process and move up into the shallow soil environment and the root zone, severely limiting crop growth and productivity (Wiebe *et al.*, 2006). In addition, salts entering the water table migrate to local discharge points where they concentrate due to evaporation, contributing to the progressive concentration of soil salt in the shallow subsurface (Wiebe *et al.*, 2010).

The role of irrigation in the degradation of surface waters and groundwater within the Canadian context is in general very poorly understood and documented. Adverse effects are spatially variable and depend on soil properties; while problems may not arise in well-drained soils, significant problems are likely to occur in poorly drained soils. Considering the crippling economic effects that these impacts have had elsewhere in the world (see Jolly *et al.*, 2001 for an Australian example), enhanced monitoring and in-field assessment will be essential to assess the current and future magnitude of these regional threats to water quality, specifically in the Prairies where irrigation intensity is likely to increase.

Enhanced Drainage

Drainage of agricultural lands has been a significant factor in the opening of new arable land and in maintaining crop productivity in wetter regions. Across Canada, enhanced surface drainage for agricultural land use has been extensively practised (Van der Gulik *et al.*, 2000). Considering the large land areas involved, modifications to natural drainage within the agricultural landscape can impact both water quantity and quality at the watershed scale. For example, in Canada's Prairie provinces, concerns have been expressed regarding the loss of wetlands and the subsequent changes in hydrologic connectivity (Pomeroy *et al.*, 2010). However, the Panel observes that although the physical processes associated with enhanced drainage activities are well understood and used for design considerations, the local and regional cumulative impacts are poorly documented due to a lack of data and supporting studies. In addition, the Panel notes that regulatory control and governance of drainage works are inconsistent across Canada.

Improvements in land drainage are generally achieved by clearing and enlarging natural channels and excavating the shallow ditch networks that drain into these natural channels and by installing permeable tubes or tile drains in the shallow subsurface. The goals are to accelerate the removal of excess surface and shallow subsurface waters during spring melts and heavy precipitation, to facilitate access to fields for cultivation, and to control the position of the water table to allow for optimal plant growth. The significance of these combined components of enhanced drainage within the Canadian agriculture landscape is addressed below.

Impacts of Drainage on the Environment

The destruction of the natural wetland areas as a consequence of enhanced drainage in agricultural landscapes has been acknowledged on a global scale (Verhoeven & Setter, 2010). It is also likely to continue as the demand for agricultural land continues to grow. The impacts of this include a reduction in wildlife habitat, which may also influence species diversity (Dahl & Watmough, 2007). The magnitude of these impacts and the longer-term consequences for ecologic health and sustainability are not well understood. At the same time, the value that society places on wildlife habitat and species diversity is becoming a considerable factor in the long-term management of watershed systems. However, a sufficient, science-based understanding of many of the key controlling processes required to manage agricultural drainage to mitigate these impacts is lacking.

Wetland areas retain water and hence mitigate downstream flood risk and provide a degree of drought resilience. Historical evidence suggests that First Nations peoples protected beavers because of their role in creating wetlands that provided water for migrating bison under drought conditions (Marchildon, 2009). Wetlands also function as natural sinks for nutrients moving within the shallow hydrological system through the combined processes of chemical and biologic attenuation (Cey *et al.*, 1999). If wetlands are reduced or removed, the landscape loses part of its natural capacity to absorb excess nutrients from crop over-fertilization. This results in a potential increase in residual nutrients within the shallow subsurface and a subsequent degradation of surface water and groundwater quality. Recent studies in southern Saskatchewan have shown the impacts of the artificial drainage of prairie potholes on water and nutrient balances (e.g., Pomeroy *et al.*, 2010). The intrinsic value of wetland areas in maintaining a sustainable nutrient balance in agricultural landscapes remains a challenge to quantify and a topic in need of additional research.

Impacts of Drainage on Water Quality

Strategies that enhance drainage naturally target shallow waters, which often have the highest concentrations of agrichemicals in the agricultural environment (Rozemeijer *et al.*, 2010). Of particular concern is the capacity of drainage ditch and tile drain networks to rapidly route surface and near-surface runoff waters and shallow groundwater to larger receiving bodies such as streams and lakes. The tile drains essentially skim soil water and groundwater from the near-surface region and direct it to surface water channels to maintain the water table level beneath the cultivated land at a point that enhances crop health and permits safe vehicle access. Part of the excess nutrients and pesticides that leach past the root zone into the water table may seep into adjacent surface water bodies through the subsurface drainage system. As a result, downstream surface water has been shown to have elevated levels of nutrients and turbidity (Rozemeijer *et al.*, 2010). Chronic nutrient flux to the surface water drains has been shown to result in eutrophication in local surface waters and continuous nutrient load to downstream surface water bodies (Howarth *et al.*, 2011).

Tile drain networks tend to respond rapidly to extreme climatic events such as precipitation and snowmelt and to the application of liquid fertilizers such as manure slurries (Frey *et al.*, 2012). During such events, high concentrations of contaminants are frequently flushed through the tiles to receiving surface water drains. This poses a threat to surface water quality and influences the health of the aquatic environment and downstream receptors (WEBs, 2010). Despite the prevalence and continued expansion of the integrated tile drain and surface drainage systems — in Ontario alone, over 45 per cent of the arable land is tile drained — the current and future impacts on water quality, which may be a major factor influencing water quality degradation on a regional scale in the agricultural landscape, are poorly understood. This is a priority area in need of additional scientific research.

4.3 BENEFICIAL MANAGEMENT PRACTICES

Having presented the potential adverse effects of agriculture on the quantity and quality of water resources and on the health of aquatic ecosystems in Chapter 3, and addressed the specific issues associated with land use and land management change, including irrigation and drainage in the sections above, the potential for agriculture to mitigate these effects and to preserve and enhance environmental quality is explored below. Not only does the long-term sustainability of agriculture depend on maintaining healthy ecosystems, but there is an important broader perspective for Canadian agriculture in the provision of ecosystem goods and services. In response to growing understanding of potential adverse effects, the Canadian agriculture sector applies what have come to be known as Beneficial (or Best) Management Practices (BMPs) (Corkal & Adkins, 2008). BMPs can be defined as a range of "practical, cost-effective methods that minimize environmental impacts" of activities such as agriculture (Government of Alberta, 2011). In this section, the utility and application of BMPs in Canada, the adequacy of the Canadian science base for quantifying their impacts on water quantity and quality, and international perspectives are considered. In the following section, BMPs are set in the context of conservation agriculture, and consider further the role of agriculture as a provider of ecosystem goods and services.

There are a wide range of BMPs for cropping and livestock production, many of them related to water issues (MacKay & Hewitt, 2010). MacKay and Hewitt (2010) note that the adoption of BMPs may aid in achieving greater and more reliable production through improvements in water use efficiency as well as resilience to both drought and excess water, to which can be added improved efficiencies in nutrient and pesticide applications, with associated environmental and economic benefits. They note that several of the key benefits of implementing BMPs include reducing erosion and maintaining clean water (MacKay & Hewitt, 2010). Targeted BMP strategies have also proven effective at preserving water quality in surface water systems (Detenbeck *et al.*, 2002) and in providing a broad range of ecosystem benefits (Yates *et al.*, 2007).

A 2006 Farm Environmental Management Survey (FEMS) (Statistics Canada, 2007) showed that producers across Canada implemented a number of BMPs to manage manure, fertilizers, and pesticides and protect land and water resources (MacKay & Hewitt, 2010). Nutrient management practices, including soil testing, optimizing application timing, incorporation of manure, and increased on-farm storage capacity, have been adopted in some areas of Canada; however, their performance characteristics remain largely unknown (MacKay & Hewitt, 2010). In 2006, 34 per cent of farmers planted permanent perennial forages on erodible land, 31 per cent had farmstead shelterbelts, and 20 per cent had field shelterbelts. In addition, cover or companion crops were seeded by 23 per cent of farmers and 11 per cent planted winter cover crops (MacKay & Hewitt, 2010).

Several government-based programs have been coordinated across Canada over the last decade to facilitate the knowledge transfer and implementation of BMPs on individual farms. For example, the Environmental Farm Planning (EFP) process, managed jointly through Agriculture and Agri-Food Canada and provincial authorities, is a key source of information and education for farmers in Canada that provides a framework to support BMP implementation. In 2006, 28 per cent of farms in Canada had a formal written EFP and another 10 per cent had plans under development (MacKay & Hewitt, 2010). Due to confidentiality issues, however, complete evaluation of the effectiveness of the EFP program relative to BMP implementation and performance is not readily available.

The effectiveness of BMPs is discussed in detail below, but it should be noted that the evidence is mixed. In a comprehensive BMP and watershed quality study in southern Manitoba, Li *et al.* (2011) quantified the effectiveness of BMPs in protecting water quality and noted that the collective reduction of nutrient losses from these BMPs was substantial. BMPs for livestock management are also effective at protecting water quality (Hubbard *et al.*, 2004). However, Jarvie *et al.* (2010) noted the importance of considering site scenarios with respect to soil type and illustrated, for example, that intensive livestock farming on heavy clay soils resulted in dramatically higher stream diffuse-source total phosphorus yields. Kemp and Michalk (2007) noted that long-term, economically optimal stocking rates can be linked with enhanced environmental outcomes. Therefore, it is apparent that an important characteristic of BMPs is that local conditions must be recognized in design and implementation of BMPs, the effectiveness of which is very much dependent on the local context of soils, climate, and land management practices.

National funding programs have recognized about 30 BMPs that differ in effectiveness and popularity (Sparling & Brethour, 2007). The evidence of some practices, for example, no-till agriculture, off-stream watering (Godwin & Miner, 1996), and nutrient management planning (Hickey & Doran, 2004; Larson, 2007) appear promising, while many (e.g., conversion to perennial cover and buffer strips) require further validation (AAFC, 2010b; Hickey & Doran, 2004). Certain BMPs are more commonly used in different regions of Canada, reflecting the local nature of agricultural production; improved cropping systems involving lower soil disturbance or improved fertilizer application methods are common in the Prairies and increasing in popularity in Ontario, while farmers in Atlantic

Canada have improved manure storage, erosion control, and product and waste management practices (Sparling & Brethour, 2007). In British Columbia, farmers have focused on irrigation management, while shelterbelt establishment and riparian area management are common in Quebec (Sparling & Brethour, 2007).

As illustrated by the example from P.E.I. (see Box 4.1), promotion of BMP adoption through encouragement and incentives can help facilitate the adoption of such practices and enhance stakeholder collaboration and uptake. However, the ability of these practices to reduce environmental risk and improve environmental conditions can vary across field sites, making a nationwide synthesis of BMP efficiency extremely difficult (Easton *et al.*, 2008; Gitau *et al.*, 2005; Sharpley *et al.*, 2009).

Box 4.1

Prince Edward Island: The Shift from a Legislative to a BMP Approach

Prince Edward Island is the smallest province in Canada, with an area of 5,660 km^2 and a population of 145,900 residents who depend entirely on one aquifer for their fresh water supply. The size of the island allows for implementing province-wide reforms and monitoring water contamination. P.E.I. first recognized the need for agricultural policy reform in the late 1990s, when the negative effects of some agricultural practices (e.g., pesticide and fertilizer contamination) became more evident. In 1999, there were eight recorded fish kills as a result of pesticide contamination of water, up from one in 1998 (Prince Edward Island Department of Environment, Energy and Forestry, 2011). The fish kills provoked significant public concern and also risked the health of the island's sport fishery. Evidence pointed to the contamination being due to pesticides adhering to soil particles in runoff water. More recently, attention has been focused on elevated nitrate concentrations in the groundwater linked to fertilizer used in potato production. Nitrates may cause a human health risk when the concentration exceeds the maximum acceptable concentration of 10 mg/L NO_3-N (Health Canada, 2010).

In the late 1990s to early 2000s, the need for change was addressed using a legislative approach, with several laws being passed designed to push farmers into implementing more environmentally friendly practices to protect groundwater, prevent soil erosion, and enhance biodiversity. These included amendments to the *Environmental Protection Act*, introduced in 1999, which mandated a 10-metre buffer zone and 50-metre

continued on next page

conservation zones. Restrictions limiting row crops on high slope land were also introduced, as was crop rotation legislation, which dictated that potatoes could only be grown on a parcel of land once every three years. While some incentives were included in this legislative approach, the laws were impossible to enforce as the government did not have the resources to monitor every crop on the island. The approach also contributed to a strained relationship between government and producers, with farmers feeling under attack.

The mid-2000s saw the beginnings of a shift away from the legislative approach towards a BMP-driven approach, which favoured encouragement over punishment. The Canada-P.E.I. Agricultural Stewardship program was introduced in 2006 with the intention of helping farmers improve their farms by providing them with technical and financial support. To participate, farmers must have had an Environmental Farm Plan (EFP) completed or updated within the previous five years. The EFP provides an environmental assessment of the operation to identify priority areas for improvement. The 40 BMPs included in the Stewardship program are wide-ranging, from using global positioning systems (GPS) units on tractors, to purchasing improved manure spreaders, to hedgerow/buffer zone planting. Modifications to the program have been made to ensure that retailers are not taking advantage of the changes and that it is farmers who see the benefits. Farmers are able to receive between $6,000 and $35,000 per project, depending on the BMP, with a total maximum of $50,000 over a four-year period (Canada-P.E.I., n.d.). The program, which was renewed in 2009 and is expected to run until 2013, receives 200 to 250 applications per year. Another financial incentive linked to BMPs is provided through a reduction in crop insurance premiums; producers received a 6 per cent discount on their 2010 crop insurance premiums if they participated in the nutrient management planning BMP and purchased lime for one-third of their insured acreage.

P.E.I.'s experiences have been that a purely legislative approach was not sufficient to bring about the changes in agricultural practices needed to protect the soil health, water quality, and wildlife habitat in the province. A holistic approach that includes support for BMPs, soft cross-compliance mechanisms, and advocacy has been found to be more effective in bringing about environmentally positive change to farming practices.

The Panel notes that a further important lesson from the P.E.I. experience is that while uptake of BMPs has been impressive, and there are strong perceptions that these have been successful interventions, nevertheless the scientific evidence to quantify regional impacts remains largely lacking.

Evaluating BMPs

The Panel maintains that to ensure a sufficient economic, environmental, and social return on investment, the efficacy of BMPs needs to be systematically evaluated. Pioneering studies related to the causes of non-point-source releases of nutrients and impacts on surface water courses — specifically the Great Lakes — were derived from the extensive work carried out in the 1970's by the Pollution from Land Use Activities Reference Group (PLUARG) (PLUARG, 2010). The results from this work clearly illustrated the complexity associated with the release of agriculturally-derived nutrients and also demonstrated the initial potential of remedial measures that might be adopted to reduce impacts to surface water quality in the agricultural landscape, amoung other land uses. This program was followed up by the Soil and Water Environmental Enhancement Program (SWEEP) (SWEEP, 2010) conducted through collaboration between AAFC and the Province of Ontario in the mid 1980s. This program focused directly on strategies to reduce the release of phosphorous to Lake Erie from agricultural fields through the adoption of soil conservation and related BMP approaches. AAFC and Environment Canada began evaluating BMPs in a broader context in 2004 through such programs as the National Agri-Environmental Standards Initiative (NAESI) (Environment Canada, 2010b) and the Watershed Evaluation of BMPs (WEBs) project (AAFC, 2010b). These programs have helped to understand the effectiveness of BMPs across practices and informed the selection of BMPs to meet environmental standards. A BMP Adoption Index has also been developed as a macro-level indicator of average BMP adoption in each region across Canada (MacKay *et al.*, 2010).

NAESI identified both ideal and achievable levels of environmental quality (AAFC, 2008). Ideal performance standards (IPS) defined a long-term goal for the desired level of environmental quality, while achievable performance standards (APS) described the level of environmental quality achievable through applying BMPs and/or other land management practices (Environment Canada, 2010b).

As achieving any IPS or APS would require a collective approach to BMPs within a geographical area, through the National Farm Stewardship Program, NAESI identified an approach to select the most effective type and/or location of BMP to progress towards ideal water quality (Environment Canada, 2010b). However, the NAESI initiative was to guide the selection of BMPs, and it did not possess metrics to analyze the success and long-term effects of BMP implementation at the watershed level. In contrast, the WEBs project specifically aims to evaluate the impacts of selected BMPs on water quality, which often reflects other environmental indicators (i.e., soil and air quality and biodiversity). Focusing on nine small watersheds across Canada (between about 300 and 2,500 hectares), each WEBs study involves the following components:

- biophysical evaluations to measure environmental impact;
- economic evaluations to assess the costs and benefits of implementation; and

- hydrological modelling to assess contaminant transport and potential impacts of BMP performance at the watershed scale.

(AAFC, 2010b)

The combination of hydrological and economic considerations has also been incorporated into a decision-support tool for long-term watershed planning: integrated modelling frameworks have been created for pilot sites in Manitoba and Quebec, with other sites looking to follow suit (AAFC, 2010b). A comprehensive picture of BMPs by watershed from the WEBs program is given below (Table 4.1).

Table 4.1

BMPs by Watershed

WEBs		BC	AB	SK	MB	ON	QC	NB	NS	PE
BMPs		SR	LLBR	PC	STC/S	SN	BH&F	BB	TB	SR
RIPARIAN	Cattle exclusion fencing (and off-stream watering)	X	X			X			X	
	Off-stream watering without fencing		X							
	Riparian vegetation management				X					X
IN-FIELD	Nutrient input/ management (commercial fertilizer, manure)		X	X			X		X	
	Tillage/crop residue management				X		X			X
	Crop rotation						X			
	Perennial cover			X	X					
	Reduced herbicide use						X			
	Winter bale-grazing			X	X					
	Irrigation efficiency	X								
RUNOFF/DISCHARGE	Diversion terraces and grassed waterways							X		
	Surface runoff control measures						X			
	Buffer strips		X					X		
	Farmyard runoff management								X	
	Runoff retention pond				X				X	
	Small reservoirs				X					
	Wetland restoration			X						
	Controlled tile drainage					X				

Source: AAFC, 2011d

SR = Salmon River; LLBR = Lower Little Bow River; PC = Pipestone Creek; STC/S = South Tobacco Creek/Steppler; SN = South Nation; BH&F = Bras d'Henri and Fourchette; BB = Black Brook; TB = Thomas Brook; SR = Souris River.

The most recent review of the WEBs program noted that, of 22 BMPs investigated, 13 clearly showed potential to reduce contaminant loading of surface waters, but "in many cases, the degree of this effectiveness has yet to be quantified" (AAFC, 2010b). It is important to note that the BMPs studied in the WEBs project were chosen to match the individual conditions of each watershed and to reflect local and regional BMP interests; the project was therefore not originally intended to compare BMP effects across a wide range of landscape and watershed conditions. The fact that some BMPs were applied in more than one watershed did, however, allow for a preliminary assessment of multi-site effects as well as the development of models quantifying the effect of BMPs on the watershed. However, apart from the lack of quantification of local-scale results, it is important to note that the scaling up of the results to provide catchment- and regional-scale assessments is a complex task. AAFC (2010b) notes that scaling of the impacts requires further validation based on local and regional field data and the strengthening of the national network of watershed-scale laboratories by adding new sites to address identified landscape gaps. It is also critical to point out that both the NAESI and WEBs programs have focused almost exclusively on surface waters with little specific consideration of the influence of the BMP programs on groundwater resources. The Panel considers this to be a significant gap in focus in need of additional scientific consideration and in-field assessment.

Industry is also active in developing BMPs that help mitigate the negative impact that agricultural activity can have on the environment. The application of fertilizer, for example, is one area where industry has worked on developing effective BMPs for farmers. The Canadian industry focuses on the "4Rs" associated with fertilizer application: the right product, right rate, right time, and right place (Rawluk & Racz, 2009) (see the technologies discussed in Chapter 5). The development of polymer-coated urea for example is designed to release nutrients in a time lagged fashion in order to enhance effective plant uptake and reduce leaching losses (Hyatt *et al.*, 2010; Wilson *et al.*, 2010). Slow-release fertilizer technologies deployed in accordance with the crop growing cycle may offer significant advantages in optimizing nutrient use efficiency, especially in the temporally variable hydrologic conditions associated with Canadian seasonality. According to the International Plant Institute, the 4R approach taken by the fertilizer industry takes into consideration the "economic, social, and environmental dimensions of nutrient management and is essential to sustainability of agricultural systems" (International Plant Nutrition Institute, 2012).

International Perspectives Related to Nutrient Management BMPs

In many parts of the world, there has been a long history of highly intensive agricultural land management and considerable experience with BMP policy and implementation. For example, Europe has experienced the intensive use of both fertilizers and manures over extended time periods and suffered the environmental consequences (Oenema *et al.*, 2009). In 1991, the Council of the European Community introduced a nitrates directive (EU, 1991) that observed that "the main cause of pollution from diffuse sources affecting the European Community's waters is nitrates from agricultural sources." As a result, nitrate-vulnerable zones (NVZs) were designated, for which the amount and timing of fertilizer application and storage was limited (EU, 1991). The areas of land affected were very extensive, including 69 per cent of arable land and 57 per cent of managed grassland in England (Johnson *et al.*, 2011).

The environmental benefits of adopting the NVZ strategy have been inconsistent and problematic to quantify. Recent results based on microcatchments and national scale modelling showed that nitrate concentrations in leachate from arable land were typically well in excess of the limit value, even where the farmer was following best practices (Johnson *et al.*, 2011). Worrall *et al.* (2009) showed that nitrate concentrations in many rivers and groundwaters in England and Wales remain high and concluded that existing regulations have not significantly impacted nitrate concentrations in surface water. However, an official Nitrates Directive fact sheet (2010) (EU, 2010) states that the Nitrates Directive "is proving effective: between 2004 and 2007, nitrate concentrations in surface water remained stable or fell at 70 per cent of monitored sites. Quality at 66 per cent of groundwater monitoring points is stable or improving."

While the U.K. experience demonstrates that a major national policy initiative has yet to deliver convincing results of reductions in nitrate, the U.S. EPA (2011) considered the potential of management practices to reduce the loading of reactive nitrogen. Their conclusions are promising:

- Excess flows of reactive nitrogen into streams, rivers, and coastal systems can be decreased by about 20 per cent through improved landscape management and without undue disruption to agriculture;
- Crop and uptake efficiencies can be increased by up to 25 per cent of current practices by combining knowledge-based practices and advances in fertilizer technology;
- Crop output can be increased while decreasing total reactive nitrogen by up to 20 per cent of the artificial reactive nitrogen; and
- Livestock-derived nitrate emissions can be decreased by 30 per cent by a combination of BMPs and engineered solutions.

The BMPs envisaged include large-scale wetland creation and restoration, matching cropping systems and intensity of reactive nitrogen use to land characteristics, improved tile drainage systems, and riparian buffers. However, while these measures were expected to reduce concentrations significantly, the question arises as to how much reduction is needed to achieve significant environmental benefits. The EPA noted that further reductions will undoubtedly be needed (a) for many nitrogen-sensitive ecosystems, and (b) to ensure that health-related standards are maintained.

A recent European Nitrogen Assessment (Sutton *et al.*, 2011) mirrors the U.S. EPA report in many ways. It identified three key actions for agriculture:
- Improving nitrogen use efficiency in crop production (by improving field management practices, genetic potential, reduced losses);
- Improving efficiency of nitrogen use in livestock management; and
- Increasing the nitrogen equivalence value of animal manure.

However, it argues strongly that, for action to be effective, a coordinated policy is needed across all sectors of the economy.

These two major reports clearly demonstrate the challenges of meeting environmental standards for nutrient pollution, as perceived in Europe and the U.S., but they also illustrate the potential benefits of appropriate BMP deployment. This again underlines the vital need for science-based performance assessment of a spectrum of BMP strategies in order to most effectively incorporate them into a national framework for water sustainability in agricultural landscapes.

Implications of BMP Evaluation Results for Canada

While Canada has made significant investments in long-term research to evaluate the effectiveness of BMPs, definitive results remain elusive. As noted above, the most recent review of the WEBs program noted that, while many BMPs clearly showed potential to reduce contaminant loading of surface waters, “in many cases, the degree of this effectiveness has yet to be quantified” (AAFC, 2010b). In fact, the report notes that “only one BMP studied in WEBs (controlled tile drainage) has thus far clearly proven to be economically viable at the farm level.” In general, successful BMPs can be expected to offer a broad range of environmental benefits, but these are unlikely to be reflected in direct on-farm economic benefits, which remains a significant barrier to wide-spread BMP adoption.

The question remains: given the various concerns for adverse effects of agriculture on the water environment, particularly of nutrients, what is the potential for BMPs to reduce these effects to loadings? The Panel notes that (a) Canadian research (e.g., WEBs) is not yet sufficiently mature to be able to quantify the effects of the majority of BMPs; (b) reliable regional scale assessments of impacts of BMPs are not currently available, even in those areas where uptake by farmers has been extensive; and (c) there has been very little focus on the adoption and performance of BMPs designed to project groundwater quality and quantity. The latter point is applicable on a global scale. There are clear and important research gaps. However, it is important to recognize the lag time (the time elapsed between installation or adoption of management measures and the first measurable improvement in water quality in the target water body) in evaluating the implemented BMPs, as short-time evaluation might not display significant results (Meals *et al.*, 2010). This identifies the intrinsic need for long-term and continuous monitoring of field locations where BMPs have been implemented in order to develop quantifiable performance metrics.

Important social science research questions should also be noted. A better understanding of the drivers behind BMP adoption may facilitate widespread implementation. The literature suggests that producers with higher levels of education, larger farms, or higher levels of gross sales or who earn off-farm income are more likely to adopt BMPs; however, these findings are not consistent across all reported studies (Sparling & Brethour, 2007). Farmers who do not understand the need for the BMP (i.e., the potential for economic net gain) despite the availability of financial incentives for their adoption may also be an additional barrier to adoption (Curtis & Robertson, 2003). Finally, transition costs (including capital costs for new equipment and the educational costs of learning about BMPs) may also hinder adoption (Sparling & Brethour, 2007).

The challenges of conducting a cost-benefit analysis of BMPs are exacerbated by difficulties in quantifying their effects at the watershed scale and in measuring the expected return on investment. The WEBs project served as a first step in allowing for a preliminary assessment of multi-site effects, as well as the development of models quantifying the effect of BMPs at the watershed scale. However, the scaling up of the results of these models requires further validation based on field data (AAFC, 2010b) and economic modelling. Comprehensive evaluation of BMP performance will also require an investigative approach that will permit the integration of both the surface water and groundwater systems, something that has historically been lacking in Canada and elsewhere. In addition, the creation of governance mechanisms for promoting BMP uptake is an important area for further research to encourage the use of those practices that have been shown to improve economic, environmental, and social outcomes.

4.4 NEW PERSPECTIVES FOR SUSTAINABLE AGRICULTURE FOR CANADA — CONSERVATION AGRICULTURE AND ECOSYSTEM SERVICES APPROACH

While BMPs have much to offer in reducing environmental impacts, the extent to which significant environmental benefits can be achieved is an open question and requires extensive further research. This section introduces two related concepts: conservation agriculture and ecosystem services approach. Conservation agriculture is a response to concerns that current trends of intensification and loss of diversity have effects on the resilience of agricultural systems, and BMPs can be seen as components of this broader vision for sustainable agriculture. This is also connected to the idea that agriculture has a broader role to play than production, and, as a dominant land use, can play a key role in delivering a broader range of services to society, one to which BMPs can make an important contribution.

Conservation Agriculture

Developed from a holistic perspective, conservation agriculture can include a range of practices integrated within a systems approach to farming. Because farming is the management of living systems, and sustainable agriculture is reliant on a living and finite soil resource, conservation agriculture presents a unique challenge.

Much of the agricultural development that has occurred since the 1960s has emphasized scale at the cost of diversity and integration within systems (Pretty, 2008). Typical agricultural systems separate livestock from crop farming, often separating, in both time and space, feed from the animals consuming it and manure from the land on which it could be used (Russelle *et al.*, 2007). Farms are now technology intensive, but have low agronomic and biological diversity. These farms are at great risk financially because their gross income and expenses are high; with declining returns, the net income to expense ratio decreases greatly, contributing to further financial risk. These farms also face greater biological risks because simple agronomic systems (monocultures, for example) are inherently more susceptible to natural attack and are not adaptable to a changing climate (Brooks & Loevinsohn, 2011; Nazarko *et al.*, 2005).

The terms *conservation agriculture* and *natural systems agriculture* are catch-all terms for sustainable agriculture approaches. The intent behind using these terms is to draw attention to the fact that agriculture as an economic activity is particular in that the capacity of the system to deliver is dependent on the biological capacity, and that managing biological systems can provide challenges that are not faced when managing abiotic mechanistic systems. The evidence shows that variation in agricultural yield due to environmental factors far outweighs the variation in yield that results from either management or cultivars (Anderson, 2010b). This points to a need to make resilience a high priority in agricultural systems. Conservation agriculture movements encourage the creation of healthy living landscapes that are productive but also inherently resilient, robust, and restorative. The core driver for these characteristics, as it is in nature, is diversity (Cox *et al.*, 2004). Integration is also important. In terms of water, this includes connections between urban and agricultural use and recycling of water (Cubillo, 2010). Diversity and resilience in agricultural systems can be achieved through a variety of means, but some of the most common components of conservation agriculture are rotation, use of legumes, use of perennials, integrated livestock systems, and reduced tillage and soil conservation.

The following subsections describe examples of techniques that can be used for conservation agriculture.

Rotation

In Canada, long-term studies have demonstrated the value of rotation in sustaining cropping systems. Rotation provides greater resilience and more consistent performance while also supporting greater soil life and aiding weed management. These include work on conventional and organic agriculture in terms of yield and cropping systems in Manitoba (Entz *et al.*, 2002) and a broader summary of weed management studies across the northern great plains (Derksen *et al.*, 2002).

Legumes

In broad-acre crop farming, synthetic nitrogen fertilizer accounts for the vast majority of commercial energy input used to produce mineral fertilizer (Hoeppner *et al.*, 2006). Inclusion of nitrogen-fixing species into crop rotations can fundamentally alter the energy and economic sustainability of cropping systems.

Perennials

The vast majority of crops in industrial cropping systems are summer annuals. The addition of perennials to a cropping system provides functional diversity and fundamentally changes the timing of management activities in the system, which provides benefits when it comes to managing pests (Nazarko *et al.*, 2005). Furthermore, perennials have greater resilience than annuals and can achieve greater resource use efficiencies and extraction capacities than annuals (Cox *et al.*, 2010). In addition, perennials have greater potential for deep carbon sequestration. The greatest challenge in moving towards natural systems agriculture is related to the adoption and operation of new practices within existing economic and market structures. For example, cash flow is a tremendous challenge for conventional farms and the adoption of non-cash crop perennials into a cash crop rotation is financially impractical. The push at the Land Institute and at the University of Manitoba to breed perennial grain crops[30] is in part an effort to create practical opportunities for cash crop farmers to add functional diversity to their cropping.

Integrated Livestock Systems

To make carbon and phosphorus cycling in agriculture more effective, some type of re-integration between plant and animal agriculture is required (Russelle *et al.*, 2007). This type of integration can be challenging in a practical sense but there have been considerations of these practical concerns in a range of scenarios, from regions with intensive livestock operations to regions with extensive and broad scale rangeland. There is no one model that suits all scenarios but the principle of integration is acknowledged to be important in building resiliency and efficiency within farming systems.

Reduced Tillage and Soil Conservation

Reduced tillage and the broader concept of soil conservation have become movements in Canada, with development and leadership coming from farmer associations among others (Brandt, 2009). The appeal of these movements is both stewardship and comparative advantage (Baig & Gamache, 2009). As outlined in Dumanski *et al.* (2006) key principles of soil conservation include:

- Maintaining permanent soil cover and reducing the disturbance of soil to enhance water infiltration, improve soil water use efficiency, and provide increased insurance against drought.
- Promoting healthy, living soil through crop rotation, cover crops, and efficient and limited use of pesticides. This encourages natural soil biodiversity and creates healthy soil that is naturally aerated, and better able to receive, hold, and supply plants with available water.
- Feeding the soil rather than fertilizing the crop. This reduces chemical pollution, improves water quality, and maintains the natural ecological integrity of the soil.
- Promoting precision use of inputs to decrease costs, optimize efficiency, and mitigate environmental damage. Technology can help to enhance precision, but astute problem diagnosis and precise placement of treatments is the principal basis. In small-scale horticultural and farming systems, it also includes differential plantings on hills and ridges to optimize soil moisture and sunshine conditions.
- Promoting the use of legumes (to increase the use of biologically fixed nitrogen), composting, and the use of manures and other organic soil amendments. These practices improve soil structure, inherent soil fertility, and water holding capacity, and reduce soil erosion risk.

(Dumanski *et al.*, 2006)

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[30] See http://umanitoba.ca/outreach/naturalagriculture/perennialgrain.html.

The Panel notes the potential of conservation agriculture to address issues of resilience in the face of increasing uncertainty concerning climate variability and climate change, and the evident synergies with the BMPs discussed above.

An Ecosystem Services Approach

As summarized in Bennett *et al.* (2009), human populations have invested significant resources for engineering ecosystems to cheaply and reliably produce food, timber, and other (typically marketable) ecosystem services. Yet these efforts have often paid insufficient heed to the multiple, complex interactions among the ecosystem services produced within agricultural landscapes (Bennett *et al.*, 2009). This has resulted in a global increase in marketable ecosystem services such as food and timber, at the expense of many other (typically non-marketable) services, such as flood control, water quality, or disease regulation (Millenium Ecosystem Assessment, 2005). Narrow focus on a small set of ecosystem services has even led to sudden declines of other ecosystem services (Gordon *et al.*, 2008). Such declines are a growing matter of concern, coming at a time when demand for almost all ecosystem services continues to rise (Bennett *et al.*, 2009; Millenium Ecosystem Assessment, 2005).

While the relationships among ecosystem services are important, our understanding of these interactions in agricultural landscapes is poor (Raudsepp-Hearne *et al.*, 2010). Because of this, agricultural management decisions aimed at increasing yield or efficiency (e.g., increased fertilizer use, increased irrigation, changes in tillage or manure storage) often lead to declines in habitat, biodiversity, and non-agricultural ecosystem services, which may ultimately lead to declines in agricultural productivity because these ecosystem services provide the support base upon which agriculture relies (e.g., flood control, nutrient cycling, soil formation). While some interactions among some pairs of services are understood, there is a paucity of studies aimed at quantitative understanding of the effects of management decisions on multiple services, including biodiversity and habitat (Bennett *et al.*, 2009). This understanding is critical if the aim is to move forward with payment for ecosytem services schemes such as those discussed in Section 6.2.

Recent studies have called for a deeper analysis of the multiple and non-linear interactions among ecosystem services in a spatial context in order to gain the scientific understanding needed to avoid dramatic declines in some services (Carpenter *et al.*, 2009; Kremen & Ostfeld, 2005). Although scientists have examined the current and potential future status of ecosystem services (Millenium Ecosystem Assessment, 2005), calculated the value of services provided (Costanza *et al.*, 1997; Gallai *et al.*, 2009), mapped supply and demand (Deutsch *et al.*, 2007; van Jaarsveld *et al.*, 2005), and assessed threats to ecosystem services

(Tilman *et al.*, 2001), sufficient understanding of the ecology behind the links among landscape connectivity, biodiversity, and ecosystem services needed to effectively manage a portfolio of multiple services is still lacking (Bennett *et al.*, 2009; Kremen & Ostfeld, 2005).

That said, there are many regional examples of farmers acting as stewards of the environment, taking care of a landscape that is providing multiple ecosystem services. *Satoyama* is the Japanese term for the land between the mountains and the fully arable flat land; it is often managed as a sort of mixed-use, highly diverse agricultural landscape, with small villages, community-managed forests, and agricultural uses. The idea is that these landscapes have been shaped over many years through interactions of people and nature. Because of the high diversity of land use, satoyama landscapes are often highly biodiverse and provide a variety of ecosystem services. Satoyama is now recognized as of high value in Japan, and many conservation groups are working to maintain this disappearing landscape, including the Satoyama Initiative, whose "core vision is to realize societies in harmony with nature, that is, built on positive human-nature relationships" (Ministry of the Environment of Japan, 2010).

In Europe, the critical role of farmers as stewards of the environment is becoming more widely recognized. The European Commission recently published proposals for a new biodiversity strategy for 2011, outlining six priority targets to meet the EU's 2020 Biodiversity targets. The strategy emphasizes the role of agricultural landscapes, suggesting that much of Europe's agricultural land would need to be managed to maintain biodiversity and multiple ecosystem services (CAP2020, 2011).

Examples from Canada exist as well. The Alberta Riparian Habitat Management Society, more commonly known as "Cows and Fish," fosters a better understanding of how management of riparian areas can enhance landscape health and productivity, for the benefit of landowners, agricultural producers, and others who use and value riparian areas. In so doing, they promote a landscape that provides multiple services, including opportunities for grazing and animal husbandry, nutrient retention and high quality water, and carbon storage (Alberta Riparian Habitat Management Society, n.d.). The development of Ontario's Biodiversity Strategy involved multiple stakeholders and the public working together to establish a plan in which a shared responsibility is attributed to the public, communities, and sectors of society in order to preserve biodiversity despite the predicted population growth (Ontario Biodiversity Council, 2005). The strategy has two main goals: (a) "to protect the genetic, species and ecosystem diversity in Ontario;" and (b) "to use and develop the biological assets of Ontario sustainably, and capture benefits from such use for Ontarians" (Ontario Biodiversity Council, 2005). In 2011, a third goal was added: mainstreaming biodiversity, meaning the integration of biodiversity into the decision-making (Ontario Biodiversity Council, 2011).

The Panel notes that particular research requirements to support an ecosystems approach include better understanding of the impacts of agricultural activity on biodiversity. The Panel concludes that shifting our thinking about agriculture and farmers from places and people that produce food products to places and people that sustain and maintain landscapes that provide a great many services that people desire, is critical to maintaining Canada as a leader in global agriculture. Agriculture already occupies over one-third of the Earth's ice-free land surface (Ramankutty *et al.*, 2008), and pressure to expand this area is increasing with increased food demand (Foley, 2011). If farmlands are to be maintained as landscapes with a great many uses in addition to food production, the multiple ecosystem services of agricultural areas must be considered, and improved understanding of the interactions between these services developed (Bennett & Balvanera, 2007; Bennett *et al.*, 2009).

Review of Key Findings

Agriculture and the Water Environment

- Agricultural activity can contribute to environmental decline, particularly as related to the degradation of water quality and quantity. The nature of the environmental impacts varies significantly by agricultural region across Canada and requires local consideration. Agricultural intensification, the uncertainties associated with climate change, and evolving market demands are critical factors influencing water sustainability in the agricultural landscape.
- Widespread changes in crops, cropping practices, and tillage strategies have taken place across Canada, but cumulative effects on surface water and groundwater systems are poorly understood. Cropping and tillage practices designed to improve water use efficiency at the farm field level have shown promising benefits both nationally and internationally, and are priority areas for additional research within the Canadian context.
- Agricultural land management practices, including drainage, can increase flood runoff, resulting in reduced on-farm water storage and escalating downstream impacts. However, effects can vary greatly, depending on local conditions. Enhanced understanding of flood risk and management opportunities within the agricultural landscape is a key component of sustainable water management.
    - o Subwatershed-scale pilot studies focused on quantifying flood risk and effects of management practices are critical.

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- Irrigation provides important benefits for agriculture, particularly in areas of low and/or variable precipitation. These benefits are likely to be increased under a changing climate. However, irrigation represents the largest consumptive use of water in Canada and requires a thorough understanding of source water availability at a regional scale for effective management. The seasonal nature of the irrigation cycle can reduce groundwater storage volumes and the base flow rates of streams, threatening downstream water uses including ecosystem requirements during the most vulnerable time periods.
    - o Improved data on irrigation extraction volumes from surface water and groundwater sources and associated impacts on surface water and groundwater systems is vital to sustainable water management in the agricultural landscape.
- Enhanced drainage in agricultural settings is of fundamental value in improving cropping capacity and efficiency across Canada, yet it has led to extensive degradation of wetland ecosystems, and surface water and groundwater quality. A sufficient, science-based understanding of these issues is lacking, including the intrinsic value of wetlands with respect to water storage, water quality, and biodiversity.
- Although discussed elsewhere in this report, the Panel notes that the potential impacts of climate change — specifically changes in the temporal and spatial availability of water throughout the Canadian agriculture landscape — are largely unknown and represent a major threat to sustainable land and water management for all agricultural uses.

Mitigation Opportunities Through BMPs

- Canadian investment in BMP research is commendable and has shown promising results regarding the role of BMP implementation in the sustainable management of water in the agricultural landscape. Quantitative results remain elusive and specific challenges remain:
    - o Identification of the BMP strategies that represent the most effective options within the diverse agricultural regions of Canada.
    - o A requirement to provide quantifiable performance assessment of BMP options to better understand the magnitude of their potential impact on preserving water quality and quantity in the agricultural environment.
    - o Extended in-field performance monitoring in different agricultural regions.
    - o Enhanced focus on impact of BMP strategies on groundwater quality and quantity.
    - o Evaluation of governance frameworks, societal attitudes, and economic barriers related to the effective adoption and implementation of optimal BMP programs across Canada.

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Conservation Agriculture

- Conservation agriculture seeks to add diversity to agricultural production to increase the resilience of agricultural systems, and has strong synergies with many BMPs.
- More research is needed to quantify the potential advantages of conservation agriculture with respect to:
  - the mitigation of adverse effects of agriculture on water quantity and quality; and
  - the potential for enhancing resilience in the context of climate change.

The Shift to an Ecosystem Services Approach

- While, at a basic level, the role of agricultural practices in mitigating adverse effects of agricultural production can be considered, the Panel also considers agriculture to have an important societal role in sustaining a wide range of ecosystem services and enhancing environmental quality.
- To maintain Canada's role as a leader in global agriculture, it is critical to shift our thinking about agriculture and farmers from places and people that produce food products to places and people that sustain and maintain landscapes that provide a great many desirable services. However, encouraging this shift requires further research in a number of areas related to ecosystem services and the environment, particularly those aimed at helping to understand effects of management decisions on multiple ecosystem services, including biodiversity and habitat.

5

Promising Farm-Scale Technologies: Improving Water Productivity and Mitigating Environmental Impacts

- Irrigation Technologies
- Mulching
- Harvesting Rainwater and Blowing Snow
- Agricultural Waste and Drainage Water Treatments
- Use of Degraded Water Resources and Biosolids
- Genetically Enhanced Seeds, Plants with Novel Traits, and Other Biotechnologies
- Technologies to Support Precision Agriculture
- Fertilizer and Pesticide Formulation
- Plant Growth Regulators and Osmolytes
- Soil Stabilizers
- Nanotechnologies
- Livestock Technologies

5. Promising Farm-Scale Technologies: Improving Water Productivity and Mitigating Environmental Impacts

Overview

A range of technological options in irrigation, precision agriculture, reduced-risk pesticides, and other areas can contribute to maximizing opportunities and managing risks by improving water productivity, mitigating environmental impacts, and enhancing the overall productivity and resiliency of agriculture. Targeted research is needed to better understand the technological options and research priorities most appropriate to each agricultural context. Demonstration projects and agricultural extension are also necessary to increase the uptake and successful deployment of research and technological developments.

Technological developments have dramatically increased the overall productivity of agricultural systems, but key questions remain as to whether this is likely to continue into the future and whether it can be sustained following a more conservation-based, ecosystem services approach to agricultural production. However, there is a general level of optimism among international experts about future improvements in agricultural productivity and environmental quality that can be achieved. With these developments in place, it is anticipated that agriculture is quite capable of rising to the challenge of producing sufficient food for a growing world population while reducing its environmental impact in the face of the future challenges posed by water resource constraints and climate change (Angus *et al.*, 2009; Beddington, 2010; Falkenmark *et al.*, 2007; Godfray *et al.*, 2010; Jaggard *et al.*, 2010). Agricultural technologies are not an alternative or replacement to BMPs, but they complement and can enhance their effectiveness and delivery (Chapter 4). Therefore, greater emphasis on, and integration of, technology-based systems within BMPs can be envisaged in future.

In addition to new technological developments, major improvements in production are also predicted if critical problems that exist in terms of access to technology, expertise, and resources can be overcome in developing countries (Godfray *et al.*, 2010). In these countries, major increases in yield are anticipated from the effective deployment of existing technologies and knowledge (Godfray *et al.*, 2010). However, it is also widely recognized that high productivity achieved using current agricultural practices is often suboptimal in the use of resources and is accompanied by environmental degradation and reduction in natural biodiversity

(Beddington, 2010; Falkenmark *et al.*, 2007; Godfray *et al.*, 2010). Therefore, the major opportunities facing the agricultural industry must reconcile the need to increase food production while at the same time reducing resource inputs, maximizing their efficient utilization, increasing land and water productivity, and reducing environmental impacts and degradation. This will require an ongoing, long-term commitment and investment in research and development programs to refine existing agricultural technologies and management practices and develop new ones. Defaulting on this investment and responsibility will have serious consequences for the world population and the environment.

In contrast to Europe and North America, where public investment in agricultural research is declining, other countries, notably China and India, are gearing up and increasing investment in their research programs (Piesse & Thirtle, 2010). Published outputs in literature from Chinese researchers are becoming increasingly visible; it is apparent that China places significant emphasis on technology development in the area of agricultural water management with the aim of conserving more water and using it more efficiently. The public investment in agricultural research has been strategically targeted to meet the future challenges of climate change and serious regional and seasonal water deficits in China, therefore ensuring food, water, and ecological security in the country (Li, 2006; Pu-te, 2010).

Hsiao *et al.* (2007) used a process chain approach to establish the impact of systematic changes in the efficiency of water use at each step in the overall agricultural process. Since overall efficiency is an integration of the efficiencies of many component steps in the process (including water delivery, soil water extraction, transpiration, photosynthesis, and conversion to crop biomass/yield and animal products), it is more effective to make limited improvements across multiple steps rather than intensively focusing on improving only one or two steps. Therefore, distributing research resources and activity systematically among a broad range of inter-related agricultural water technologies and management practices is likely to achieve a greater overall improvement in economic water use efficiency than concentrating only on a restricted number of areas.

O’Neill and Dobrowolski (2011) identified six broad areas where agricultural research can impact water management to achieve agricultural water security, which, as defined by the USDA (2009), “describes the need to maintain adequate water supplies to meet the food and fiber needs of the expanding population — maximizing the efficiency of water use by farmers, ranchers, and rural communities.” Five areas have a critical technology and management basis and include: biotechnology, water re-use, general conservation, irrigation efficiency, and drought preparedness. The sixth area of research is related to water markets and trading. These broad areas may be expanded to include the following priority topics: biosolids and re-use of other biowastes, desalination, precision agriculture and conservation, nanotechnology, fertilizer and pesticide formulation, variable rate applicators, plant growth regulators and osmolytes, and livestock. Interdisciplinary research and the development and implementation of geospatial, biotechnological, and precision agriculture technologies linked with appropriate modelling tools provide the foundation to achieve sustainable increases in food production that also maintain environmental quality (Acevedo, 2011).

To ensure that new methods are successfully applied, high quality research should also be accompanied by comprehensive knowledge dissemination. Development through technology exchange, training, and extension is critical to effectively bring research innovations and new technologies into practice (Backeberg & Sanewe, 2006).[31] The following sub-sections examine several areas identified by the Panel as holding opportunities for contributing to sustainable water management in the Canadian agriculture sector, including irrigation technologies, biotechnologies, and technologies to support precision agriculture and nanotechnologies, among others (see Table 5.1).

Table 5.1

Overview of Technological Opportunities and Potential Benefits

Technological Opportunity	Potential Benefits
Irrigation Technologies	• Improved water productivity and reduced runoff from agriculture by way of better controls on the timing and amounts of water dispensed through irrigation systems.
Mulching	• Increased crop water productivity. • Reduced herbicide inputs.
Rainwater and Blowing Snow Harvesting	• Infrastructure or land management techniques to allow for retention of rainwater and snow to enhance water supply and agricultural productivity.
Agricultural Water Treatments	• Protect downstream water quality and ecosystem services. • Enable re-use of irrigation water.
Use of Degraded Water Resources and Biosolids	• Opportunities to conserve water and nutrients in local environments, reduce waste and environmental impacts, improve fertility of soil and water productivity, and expand geographic range of certain types of agriculture.

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[31] See also the discussion of knowledge transfer strategies in Chapter 6.

Technological Opportunity	Potential Benefits
Genetically Enhanced Seeds, Plants with Novel Traits, and Other Biotechnologies	• Improved yields per unit of land and increased nutritional/energy value per unit. • Improved drought and salinity tolerance. • Greater water and nutrient productivity. • Extended geographic range in which crops can be grown, and an extended growing season. • Improved pest and disease resistance to decrease impacts on soil and water from reduced risk/use of pesticides
Technologies to Support Precision Agriculture	• Remote sensing technologies: better understanding of weather patterns and crop needs, allowing for better timing of water usage. • Smart field technologies: improved understanding of crop needs (via remote and ground-level sensing technologies), combined with more precise application of water, nutrients, and pesticides. Enhanced precision and reduced waste, thereby improving water productivity and water quality.
Reduced Risk Pesticides	• Reduced risk to environment, users, and the public.
Plant Growth Regulators/ Biostimulants	• Plants that can withstand abiotic stresses, enabling capture of yield loss that might otherwise occur.
Synthetic Soil Stabilizers	• Stabilize the soil surface and flocculating properties, improve runoff water quality by reducing sediments, nitrogen, dissolved reactive and total phosphorus, chemical oxygen demand, pesticides, weed seeds and microorganisms in runoff from precipitation-fed and irrigated soils. • Provide soil erosion control and increased water infiltration.
Nanotechnologies	• Nano-pesticides that can be timed-released or released linked to a trigger. "Smart" delivery systems. • Nano-fertilizers that can reduce nitrogen loss due to leaching. Selective release linked to timing or environmental conditions. Slow controlled release. • Nano-sensors that can detect contaminants, pathogens, nutrients, and abiotic plant stress. More timely accurate input use and application. • Improve water retention in sandy soils and increase porosity in clay soils. • Nano-enabled water treatment techniques to remove water impurities, and potentially other water-borne particles/microorganisms.
Livestock Technologies	• Advances in feeding and breeding practices to enhance productivity, improve disease resistance (to reduce reliance on pharmaceuticals and antibiotics), and reduce environmental impact (e.g., methane production).

Note that this table is meant to provide examples. It is not intended to be comprehensive.

5.1 IRRIGATION TECHNOLOGIES

Irrigation is vital for crop production in arid regions, but also in other regions as a supplement to natural rainfall to remove uncertainty from sporadic and insufficient rainfall patterns (Brouwer & Heibloem, 1986), as is the case in Canada. Irrigated agriculture occupies up to 29 per cent of the world's harvested area (de Fraiture & Wichelns, 2010). Faurès *et al.* (2007) argue that irrigation will remain critical in supplying affordable, high-quality food in the future and estimate that its share of world food production will rise to more than 45 per cent by 2030, from a level of 40 per cent currently.

Irrigation technologies have developed to a significant extent over the past 50 years and extensive guidance and information on their design and operation is available.[32] Multi-national corporations involved in agricultural production may also provide information and guidance on good water management including the operation of irrigation systems (Unilever, 2010). Extensive guidance is available on water quality and suitability for agricultural irrigation (Ayers & Wescot, 1985), and also on the re-use of wastewater (Pescod, 1992). Thus, irrigation methods represent well-established technologies in agriculture, however, it can be argued that much of the literature relating to the technology has not been revised or updated for over 20 years and there is an urgent requirement to incorporate more recent technological developments into the guidance.

Irrigation hardware technologies and methods can be divided into surface irrigation methods, sprinkler, and drip irrigation techniques (Brouwer *et al.*, 1988). In Canada, the majority of irrigated farms use sprinkler techniques for all crop types, although drip methods are also frequently used for fruit crops (Poirier, 2009). The benefits that can be achieved by drip irrigation to accurately control irrigation water use are widely recognized in fruit and vegetable crop production, but interest is also increasing in field production of crops including alfalfa, corn, cotton, onion, potato, and processing tomato (Bisconer, 2010; Knox *et al.*, 2007). The benefits include increased yields, quality, and uniformity in addition to reduced water, fertilizer, energy, labour, and chemical costs and significantly reduced disease problems, since the plants are not wetted.

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[32] These resources include, for example, the *Irrigation Water Management* manuals published by the FAO (Brouwer *et al.*, 1985; Brouwer & Heibloem, 1986; Brouwer *et al.*, 1989; Brouwer *et al.*, 1988; Walker, 1989).

Technological solutions are also available to mitigate the problems of irrigation drainage on surface water and groundwater quality, such as providing drainage services or desalinating drainage water before discharge, which contribute to irrigation sustainability (Wichelns & Oster, 2006). However, in such cases, the costs of applying technology to achieve sustainable irrigation may be substantial and prohibitory (Pardossi & Incrocci, 2011; Wichelns & Oster, 2006).

Irrigation efficiencies are typically in the range of 30 to 50 per cent; these efficiencies represent substantial losses since improved practices can achieve efficiencies of 80 to 90 per cent (Hillel & Vlek, 2005). Estimated water use efficiency in the Eastern Irrigation District of Alberta is typically reported as 75 per cent, and this value is likely typical for irrigated agriculture in western Canada (CANCID, 1999). Overall, Hamdy *et al.* (2003) indicated that, for typical "traditional" irrigation schemes, only 45 per cent of the applied water may be used by crops, with losses as high as 50 per cent or more. According to their calculations, "assuming a typical situation where 80 per cent of total water use is for agriculture, a 10 per cent increase in the efficiency of irrigation would provide 50 per cent more water for municipal and industrial use." It is clear that the scope for potential water saving in agriculture is substantial (Hsiao *et al.*, 2007) and is therefore a good reason to develop policies to encourage it; a significant contribution to these savings will be achieved through the development and implementation of more water efficient technologies (Hamdy *et al.*, 2003). For example, the Alberta Irrigation Projects Association (AIPA) identified improvements in on-farm management and more efficient irrigation systems in the South Saskatchewan River basin as responsible for an increase in on-farm irrigation efficiencies from 60 to 71 per cent between 1990 and 1999. Simulation modelling carried out by AIPA also found that overall irrigation efficiencies could improve further with continued improvements to infrastructure, on-farm systems, and water management (Irrigation Water Management Study Committee, 2002).

Improvements have been made to the hardware technologies used to deliver irrigation (Hamdy *et al.*, 2003). Despite these improvements and the implementation of other water saving approaches, agricultural producers will be expected to continue reducing water consumption and improving or protecting the quality of water discharged from agricultural operations (O'Neill & Dobrowolski, 2011). Considerable scope remains to improve the efficiency of water utilization by reducing water wastage from point of abstraction to delivery in the field and at the plant root zone level (Hillel & Vlek, 2005). Water conveyance in closed conduits rather than unlined ditches can greatly increase efficiency, for instance.

In the future, significant technological developments will also occur in the control and management of irrigation systems (Faurès *et al.*, 2007), taking advantage of improvements in computerized automation, monitoring, and scheduling technologies to increase precision application of water through irrigation in measured real-time response to crop demand. Such technologies will adopt remote sensing techniques (e.g., infrared monitoring of canopy temperature to detect plant water stress, GPS satellite-based reflectivity sensing of the soil moisture status) as well as direct continuous root zone soil moisture monitoring, wireless sensor networks, and advanced, adaptable crop-water demand models to map treatments to spatially variable field and plant conditions (Dursun & Ozden, 2011; Pardossi & Incrocci, 2011; Privette *et al.*, 2011; Vijayakumar & Rosario, 2011). Improving the efficiency of water use will also reduce downstream impacts of drainage water discharges on the water environment by reducing the volume and salinity of effluents. In the future, irrigated agriculture will need to increase production with less water (Oster, 1997). However, there is generally an optimistic view that the problems of irrigated agriculture can be reduced by better management and improved technology (van Schilfgaarde, 1994; Wichelns & Oster, 2006). Technology development and implementation to increase irrigation water productivity will not only be vital to maintain and increase agricultural productivity in future, but also to meet the growing demands to reallocate water to the municipal and industrial sectors, and to meet ecosystem needs (Hamdy *et al.*, 2003).

5.2 MULCHING

The use of synthetic mulches to increase crop productivity by manipulating the crop and/or soil environment is a well-established practice in horticultural nursery stock, and fruit and intensive field vegetable crop production (e.g., Antill, 1990; Sanders, 2001; Sanders *et al.*, 1995; Wittwer, 1993) and plastic mulches are increasingly used in Canadian agriculture (Canada-Saskatchewan Irrigation Diversification Centre, 2007; Medina *et al.*, 2009). Soil surface mulches include coloured (usually black or white) or transparent plastic films through which the crop grows and develops. Perforated transparent films or woven membranes are also used to cover the entire crop as a floating mulch (Antill, 1990). There is also increasing interest in fluid biomulching techniques, that provide similar benefits to plastic film soil mulches, but with significantly reduced costs; as they are biodegradable in soil, they also reduce impacts associated with the disposal of plastic film waste after use (Chiellini *et al.*, 2008; Immirzi *et al.*, 2008; Immirzi *et al.*, 2009; Malinconico *et al.*, 2006; Schettini *et al.*, 2008). A disadvantage of plastic film mulches is the potential for increased soil erosion in uncovered bare soil areas between plastic strips (Sanders, 2001).

The main agronomic benefits of mulching include increasing crop yields and quality, extending the cropping season by producing earlier crops, and reducing irrigation water demand. This is achieved by increasing the crop/soil temperature, separating the harvestable parts of the crop from the soil, improving water conservation and availability by reducing evaporation from the soil surface, and increasing utilization of applied fertilizer nutrients due to reduced leaching losses (Kumar & Lal, 2012; Sanders, 2001; Sanders *et al.*, 1995). Although transpiration rates of vegetable crops may increase by an average of 10–30 per cent with mulching, over the growing season, the irrigation requirement may decrease by 10–30 per cent due to the reduction (50–80 per cent) in soil evaporation (Allen *et al.*, 1998). Shangyou *et al.* (1997) described a comprehensive strategy for the sustainable development of dryland agriculture in Northwest China and showed corn yields could be increased by 8–10 per cent by the adoption of specific mulching techniques using plastic film through improved water conservation management. More recent research in China has demonstrated improved crop yields and water use efficiency (WUE), and irrigation water savings by soil surface mulching of other major agricultural crops, including wheat and potatoes, in irrigated and dryland areas (Li *et al.*, 2004; Meng & Wu, 2010; Wang *et al.*, 2009; Xie *et al.*, 2005; Zhou *et al.*, 2011). A further advantage of soil surface mulches is the suppression of weed growth and competition, thus reducing the need for herbicidal treatments (Kumar & Lal, 2012; Sanders, 2001; Sanders *et al.*, 1995).

5.3 HARVESTING RAINWATER AND BLOWING SNOW

With increasing uncertainty over rainfall patterns in precipitation-fed agricultural areas, a key strategy to minimize the risk of a discontinuous water supply and avoid dry-spell-induced crop failures is the provision of water harvesting infrastructure (Rockström *et al.*, 2010; Srivastava, 2001). Examples include a variety of landscape features (e.g., contour ridges, ponds) or water gathering devices (e.g., water tanks, reservoirs, and dams) (Critchley & Siegert, 1991; Khoury-Nolde, n.d.). Water harvesting can be used to minimize water lost through runoff to augment water supplied in watershed systems (Sekar & Randhir, 2007; Zwart *et al.*, 2010). Some drought prone regions, such as Australia, have extensive experience in water harvesting techniques (Richardson *et al.*, 2004). At a global level, wide-scale adoption of on-farm water harvesting could: (a) contribute significantly to increased crop productivity, and (b) offset the negative impacts of climate change on agricultural production (Rost *et al.*, 2009). The introduction of water harvesting has been recently encouraged in Canada (Exall *et al.*, 2006), but more could be done to adopt these techniques to increase the availability of water resources for agricultural production in Canada.

Snow harvesting techniques also provide opportunities to increase soil water reserves, fill stock watering ponds (dugouts), and improve crop yields under Canadian field conditions (Pomeroy & Gray, 1995). In the Canadian Prairie region, for instance, the average annual precipitation received is in the range of 300 to 380 mm and, on average, about 30 per cent occurs as snow. Although the relationship between crop productivity and added water in dryland areas is highly variable, the yield of spring wheat, for example, can increase by up to 406 kg/ha per 25 mm of water added above typical base levels. The key technique to maximize snow harvesting is to increase the surface roughness of land to trap blowing snow; the three main practices employed to achieve this include: (a) shelterbelts of tall, woody plants (caragana, ash, maple or other trees) or non-woody plants (sudan grass, tall wheatgrass, uncut strips of grain) within cultivated areas, (b) stubble management practices (tall stubble, alternate height stubble, and trap strips), and (c) snow ridges. Experiments to evaluate the efficacy of these techniques showed that snow ridging is often ineffective due to mid-winter melts and the small snow trapping ability of the ridges (Steppuhn, 1981), whereas shelterbelts can be effective in some cases (Kort *et al.*, 2012) and stubble management is the most reliable method to produce an even, relatively deep snowcover over a field (Pomeroy and Gray, 1995).

5.4 AGRICULTURAL WASTE AND DRAINAGE WATER TREATMENTS

Constructed Wetlands

Constructed wetlands are low-cost, passive wastewater treatment systems that are particularly suited to agricultural applications, and are increasingly being used as a practicable and feasible alternative to more advanced and engineered treatment options (Speer & Champagne, 2006; Wood *et al.*, 2008). A constructed wetland is defined as an artificially constructed water storage basin or pond supporting aquatic vegetation and providing a biofiltration capability (Ellis *et al.*, 2003). Wetlands possess three basic characteristics:

1. An area supporting (at least periodically) hydrophytic vegetation (i.e., plants that grow in water) — the most common plant in constructed wetlands in North America is *Typha* sp. (cattail) while in Europe it is *Phragmites* sp. (common reed) (Peterson, 1998).
2. Substrates that are predominantly undrained hydric (continually wet) soils.
3. Non-soil (rock/gravel) substrates that are either saturated with water or have a shallow, intermittent or seasonal water cover.

(Tiner, 1997)

As constructed wetlands depend on passive and natural mechanisms of purification (mainly physico-chemical sorption and bioattenuation) their operational efficiency is influenced by many environmental factors, in particular temperature and precipitation (Speer & Champagne, 2006). The Canadian environment causes particular challenges including a shortened plant growing season (Speer & Champagne, 2006) and cold winter temperatures (Kennedy & Mayer, 2002). Nevertheless, there is a good deal of experimental evidence and experience in the successful design and operation of constructed wetlands for the treatment of a range of agricultural wastewaters in Canada (see Gottschall *et al.*, 2007; Hayman & Maaskant, 1994; Kennedy & Mayer, 2002; Madani *et al.*, 2010; Peterson, 1998; Smith *et al.*, 2005; Speer & Champagne, 2006; Trias *et al.*, 2004; Wood *et al.*, 2008).

Research has demonstrated the effectiveness of constructed wetlands for the removal of suspended solids and biological oxygen demand (BOD) (Smith *et al.*, 2006; Trias *et al.*, 2004), nitrogen and phosphorus (Dunne *et al.*, 2005; Gottschall *et al.*, 2007; Phipps & Crumpton, 1994; Smith *et al.*, 2006; Trias *et al.*, 2004; Vymazal & Kröpfelová, 2010; Wood *et al.*, 2008), pesticides (Gregoire *et al.*, 2009), and pathogens (Díaz *et al.*, 2010; Smith *et al.*, 2005) from different agricultural wastewaters including, for example, swine and dairy farmyard runoff, milkhouse wash water, silage/farmyard manure effluents, liquid manure, and agricultural subsurface drainage water (Dunne *et al.*, 2005; Gottschall *et al.*, 2007; Madani *et al.*, 2010; Smith *et al.*, 2006; Trias *et al.*, 2004; Wood *et al.*, 2008).

Hydrological loading rate and hydraulic retention time are the most significant operating parameters influencing the rate of contaminant removal by constructed wetland systems for agricultural wastewater treatment. For instance, high hydrological loadings reduce phosphorus removal efficiency (Smith *et al.*, 2006; Wood *et al.*, 2008) and phosphorus retention efficiency decreases in winter when hydrological inputs increase due to rainfall and snowmelt (Dunne *et al.*, 2005; Wood *et al.*, 2008). It is also necessary to carefully manage the hydraulic loading for the treatment of non-point pesticide pollution (Gregoire *et al.*, 2009). Pesticide fluxes can be reduced by 50–80 per cent when hydraulic pathways in constructed wetlands are optimized by increasing the hydraulic retention by a factor of 10, by recirculation, or reducing the flow rate. Indeed, bioremediation mechanisms operating in constructed wetlands have the potential to virtually eliminate pesticide residues from non-point-sources provided that the retention and contact time is sufficient (Gregoire *et al.*, 2009).

By contrast, small-scale systems with relatively short retention times are effective for agricultural wastewater treatment where the primary purpose is to reduce microbiological contamination. For example, Díaz *et al.* (2010) showed that relatively small wetland areas, with short retention times (<1 day) were effective at removing bacterial contamination (70 per cent) from irrigation return flows from large agricultural areas (with a ratio up to 360:1) under warm climatic conditions in California. Smith *et al.* (2005) similarly reported the effective removal of indicator bacteria (>98 per cent) by small-scale constructed wetland treatment systems receiving dairy wastewater (a mixture of manure and milkhouse washwater) under Canadian conditions, which were equally as effective during both warm and cold conditions experienced in Nova Scotia. In this case the retention times were longer, and equivalent to 95 days, but during the winter after heavy rainfall or snowmelt events, retention time decreased to 15–18 days.

Overall, Smith *et al.* (2006) reported that constructed wetlands were a promising method for treating dairy wastewater for nutrient removal on a year-round basis in Atlantic Canada. However, uncertainties remain about the mechanisms responsible for nitrogen removal in constructed wetlands. Denitrification is suspected as the principal mechanism of nitrogen removal from wastewater by constructed wetlands, but there is a paucity of measurements to confirm this (Vymazal & Kröpfelová, 2010). Constructed wetlands provide a sink for nitrogen; however, nitrogen retention may depend on the loading rate. Thus, Phipps and Crumpton (1994) reported that constructed wetlands may act as nitrogen sinks during periods of high nitrate loading, but become nitrogen sources during periods of low nitrate loading. Also, high flow systems were net exporters of organic nitrogen on an annual basis. Therefore, further fundamental research and monitoring is necessary for process optimization, in particular to quantify nitrogen transformation mechanisms, sources, and sinks.

Constructed wetlands are an effective approach to treating agricultural wastewaters for discharge into the environment to protect surface water quality and ecosystem services. However, they also have the potential to address the problems of water resource availability for irrigation. For example, Madani *et al.* (2010) described the design, construction, and operation of a wetland system for the treatment of subsurface agricultural drainage water, coupled to a storage reservoir for irrigation, and demonstrated that the approach improved water quality and could more than supply the water demands of the irrigation area. However, the stored water did not always meet the microbiological standards set by irrigation water guidelines. As constructed wetlands are effective at removing fecal indicator bacteria, it seems likely that secondary contamination due to inputs from wild animals and birds could provide a possible explanation for the variable microbiological quality of treated water during storage.

A further benefit of constructed wetlands is the potential to create habitat for wildlife. However, constructed wetlands are designed specifically to retain pollutants and, consequently, inputs of contaminants present in wastewaters (e.g., potentially toxic elements, pesticides, veterinary pharmaceuticals) may accumulate and cause deleterious effects on wildlife (Kennedy & Mayer, 2002). This is more likely to be an issue for municipal and industrial wastewaters compared to agriculture. However, the fate — and significance for wildlife and the environment — of potential contaminants in agricultural wastewaters treated by constructed wetlands should be assessed (Kennedy & Mayer, 2002). The scenario of restoring natural prairie wetlands was examined by Pomeroy *et al.* (2010) in a modelling study that suggested a substantial reduction in water yield and contributing area from a prairie pothole basin was possible, which might also have impact on water quality.

Permeable Barriers and Filters and *in situ* Denitrification Systems

Alternative approaches for the removal of nitrogen and phosphorus from agricultural wastewaters include engineered permeable interception barriers or filter systems that bioattenuate or retain these nutrient contaminants.

Nitrogen is attenuated by a combination of biologically mediated oxidation and reduction processes in different zones of the barrier or filter depending on whether the input mineral nitrogen content in the wastewater is in oxidized or reduced forms. Ammoniacal-nitrogen is initially oxidized by aerobic nitrifying bacteria and nitrified-nitrogen is removed under an anaerobic phase by biological denitrification processes. Wood chips are used as the microbial support media for nitrogen removal and also provide the organic carbon source for heterotrophic biodenitrification under anaerobic conditions (Ergas *et al.*, 2010; Robertson *et al.*, 2007; Ruane *et al.*, 2012;). Immobilization by microbial biomass would also appear to be a potentially important mechanism for the bioattenuation of nitrogen in aerobic filter systems (Ruane *et al.*, 2012). Woodchips are also an effective filtration medium for the removal of suspended solids and chemical oxygen demand (COD) from agricultural wastewaters (Ergas *et al.*, 2010; Ruane *et al.*, 2012).

In contrast to nitrogen, chemical sorption is the principal mechanism of phosphorus removal from wastewaters and is achieved by constructing barriers made from materials with high phosphorus binding and retention properties. Iron and aluminium-based minerals and sludges demonstrate considerable phosphorus binding potential and are typically used for this purpose. This also provides opportunities for the re-use of secondary resources with large iron and aluminium concentrations including, for example, ochre sludge from minewater treatment (Heal *et al.*, 2004) or cleanwater byproducts from the treatment of potable waters (Babatunde & Zhao, 2007; Ippolito *et al.*, 2011; Miller *et al.*, 2011; Stoner *et al.*, 2012; Zhao & Yang, 2010).

Direct injection of a simple, soluble carbon source (e.g., acetate) into the subsurface environment provides an alternative method of nitrogen removal by stimulating natural *in situ* biological denitrification activity in groundwater systems (Cartmell *et al.*, 2000; Smith *et al.*, 1999; Tompkins *et al.*, 2001). This technique offers a potentially viable option for treating high nitrate groundwaters *in situ* in the vicinity of high capacity municipal potable abstraction wells (Gierczak *et al.*, 2007).

On-Farm Pesticide Bioremediation Systems

Disposal of low-concentration pesticide residues from leftover pesticide mixes, sprayer equipment rinse water, or contaminated water for other general clean-up operations represents a potentially important point-source of surface water and groundwater contamination by agricultural pesticides (de Wilde *et al.*, 2007). However, on-farm bioremediation techniques provide an effective approach for the treatment of point-sources of pesticide-contaminated wastewater. Typically, these are engineered bioreactors containing soil or other solid organic substrate (e.g., compost, straw, or peat). Four systems have been extensively described and reported: (a) the soil-based bioreactor; (b) the biobed; (c) the Phytobac; and (d) the biofilter (de Wilde *et al.*, 2007; Hart *et al.*, 2012; Yoder *et al.*, 2001). Typical treatment efficiencies are reported to exceed 95 per cent and may achieve more than 99 per cent removal (de Wilde *et al.*, 2007; Yoder *et al.*, 2001)

Biobeds have the simplest construction and consist of a clay-lined excavated area filled with the bioreactive matrix. The Phytobac system is similar to the biobed, except that it has an engineered concrete or geomembrane lining to prevent downward water movement. Biofilters are the most sophisticated system and consists of a series of containment vessels connected in series (typically three, each with a volume of 1 m^3) containing the bioreactive matrix. Biofilters have the advantage that they can treat large volumes of effluents and provide more flexibility in system design. The performance of biobeds for on-farm remediation of pesticide waste has been recently evaluated in Canada (Wolf, 2012).

Based on a critical review of on-farm bioremediation systems for pesticides, de Wilde *et al.* (2007) observed that certain pesticides, and fungicides in particular, may accumulate in biobed type treatment systems, and therefore recommended further research to determine: (a) the pesticides or the groups of pesticides that are likely to accumulate; (b) the risk of pesticides becoming mobile during the lifetime of the biobed; and (c) the degradation time of pesticides in the waste of the biomix after dismantling the biobed. Further research is also needed on the use of microbial bioaugmentation methods to potentially enhance the rate of pesticide degradation.

The application of pesticide wastewater on land is also a common approach for disposing of sheep dip chemicals, such as diazinon, one of the main organophosphate pesticides used in sheep dip in the U.K. (DEFRA, 2001; Environment Agency, 2003). However, this is only acceptable following strict guidance and environmental control measures to protect water resources (DEFRA, 2001). For example, spreading is not permitted if the land is waterlogged or frozen, cracked following dry weather, or has been recently drained (DEFRA, 2001). Following an multi-criteria assessment of different pesticide disposal options, Al Hattab and Ghaly (2012) showed that, on balance, land application was the most practicable, effective and economical method for the disposal of pesticide wastewaters. However, as would be expected it does not provide for pesticide containment, therefore it is essential that appropriate application management practices are followed.

Slow Sand Filtration

Slow sand filtration (SSF) is one of the earliest types of potable water treatment process (Iwasaki, 1937), and it remains an important unit treatment method for improving the physical, biological, and chemical quality of water. The high efficiency of water treatment achieved by slow sand filters is partly explained by the slow filtration rate (0.1–0.3 m/h) and fine effective size of the sand (0.1–0.3 mm), but is also attributed to biological processes in the layer of slime material that accumulates above the sand surface (*schmutzdecke*) and within the upper layers of the sand bed (Campos *et al.*, 2002; Huisman & Wood, 1974). Therefore a combination of physico-chemical and biological processes are responsible for water purification and this leads to high levels of removal of enteric pathogenic microorganisms from drinking water treated by SSF (Campos *et al.*, 2002). These characteristics also mean SSF is among the most suitable and effective processes for treating and reducing the risk from plant pathogens that accumulate in recirculated irrigation water in intensive and protected horticulture systems (Calvo-Bado *et al.*, 2003; Hunter *et al.*, 2012; Pettitt & Hutchinson, 2005). Therefore, SSF enables the recirculation and re-use of spent irrigation water and nutrient solutions, thus reducing both water wastage and leaching or discharge of nutrients into ground or surface water systems.

5.5 USE OF DEGRADED WATER RESOURCES AND BIOSOLIDS

Using recycled wastewater and biosolids on agricultural land closes local water and nutrient cycles at minimal cost and energy input, and contributes to sustainable development (Langergraber & Muellegger, 2005). In some regions suffering from water scarcity, agricultural production would not be possible without irrigation using municipal wastewater (Qadir *et al.*, 2007). In Canada, water re-use is currently undeveloped as a resource, although there is extensive experience in the practice for agriculture and other land uses (Exall *et al.*, 2006). However, the pressures of climate change and other factors influencing water resources are likely to be a stimulus for expanding the reclamation and re-use of wastewater in Canada (Exall *et al.*, 2006). Agricultural use of biosolids is also widely practiced internationally (see Table 5.2). Typically, 30 to 40 per cent of the total sludge produced by urban wastewater treatment plants is recycled to agricultural land. This is true even in Canada, although provinces vary significantly in terms of the proportions and amounts of biosolids recycled to land (LeBlanc *et al.*, 2008).

Both wastewater and biosolids are recognized as potential sources of infectious pathogens and chemical contaminants, so they must be used responsibly. However, their use in agriculture is extensively researched and is usually controlled by statutory regulations and/or advisory standards supported by comprehensive advice, codes of good agricultural practice, and risk assessment that demonstrably protect human health and the environment (Pescod, 1992; Qadir *et al.*, 2007).

Table 5.2

Summary of Current Sludge Production and Use Estimates in Agriculture in Canada Compared to Different International Regions

Region or Country	Year	Total annual production (t DS)	Quantity used in agriculture	
			t DS	%
EU27	2007	10,129,500	3,934,660	39
U.K.	2008	1,372,995	1,112,738	81
Australia and New Zealand	2008/09	380,000	114,150	30
U.S.	2004	6,513,000	2,354,000	36
Canada	2002	780,175	259,800	33

Source: LeBlanc et al., 2008; Salado, 2009

*Data from each EU member country are given for a one-year period from 2002–2007.

5.6 GENETICALLY ENHANCED SEEDS, PLANTS WITH NOVEL TRAITS, AND OTHER BIOTECHNOLOGIES

Solutions to the challenges facing agricultural water management will depend increasingly on biotechnology, particularly in the areas of biowater saving,[33] crop productivity, and WUE, drought and/or salinity tolerance, pest and disease tolerance/resistance, and nutrient efficiency. Biotechnology can also contribute to increased yields and sustainability by manipulating crop root architecture and beneficial plant microbial interactions, and by detecting plant stress responses to assist precision agriculture. Conventional plant breeding, supported by plant genomic research and gene technology, is expected to offer major potential opportunities to reduce resource consumption and increase efficiency in, and sustainability of, agricultural systems into the future (Kern, 2002).

Crop Yield Potential

Beddington (2010) observed that agricultural yields are far below their potential maximum values, even in developed countries such as the U.K. For example, yields of wheat and oilseed rape in the U.K. are only at approximately 40 per cent and 35 per cent of the respective theoretical potential of current crop varieties. Jaggard *et al.* (2010) pointed out that there are also large variations in yields obtained on different farms that cannot be attributed to soil type, region, or resource inputs. They suggested that these may be weakly associated with water availability, but that the most likely reason was damage to the soil structure caused by carrying out operations in the field under inappropriate conditions. Consequently, improving basic crop and soil husbandry practices could significantly contribute to an increase in current cropping performance. However, Jaggard *et al.* (2010) are optimistic that significant increases in crop productivity will be achieved in the future primarily through plant breeding and transgenic technologies to increase potential yields, tolerance or resistance to pests and diseases, and extraction/utilization of nutrient and water resources. With improved agricultural technologies and crop varieties, they estimated that food production may be increased by 50 per cent by 2050 compared to the current situation. However, there is a great deal of uncertainty in these predictions; Molden *et al.* (2007c) concluded that only moderate potential improvements in crop water productivity may be realized through plant genetics in the next 15 to 20 years, and that greater gains are possible through better management practices.

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[33] Biowater saving: "to increase water use efficiency of crops or crop yield per unit of water input" (Wang *et al.*, 2007).

Drought Tolerance and Biowater Saving

Water limitation has a significant impact on plant productivity and crop yield. However, some plants have evolved physiological mechanisms to overcome this limitation and there is considerable optimism about the potential opportunities provided by genetically enhanced seeds and other biotechnologies to significantly increase drought tolerance, biowater saving, and yield by introducing these traits into new, improved crop cultivars (Cattivelli *et al.*, 2008; Xoconostle-Cazares *et al.*, 2010; Zhengbin *et al.*, 2011).

Conventional breeding techniques are slow, have a high resource demand, and are less successful at introducing low heritability traits such as drought tolerance (Khan *et al.*, 2011). However, advances in genomics have increased understanding of the genetics of drought tolerance, enabling quantitative trait loci to be identified and linked with DNA markers to help breeders develop high yielding, drought tolerant cultivars (Khan *et al.*, 2011). While genes that when transferred into crops do result in improvements in WUE and drought tolerance have been identified, a lack of knowledge remains regarding molecular mechanisms for WUE and drought tolerance (Zhengbin *et al.*, 2011). Nevertheless, expert opinion is that crop WUE can be substantially improved by a combination of traditional breeding techniques and the introduction of modern biotechnology (Zhengbin *et al.*, 2011). The target traits will be both physiological and morphological, including root architecture as well as perennial grains (Kell, 2011; Kunzig, 2011). Improvements in drought tolerance achieved by conventional breeding, marker-assisted breeding and transgenics have been reported for the following major crop types: maize, wheat, barley, rice, cotton, sorghum, millet, soybean, and common bean (Xoconostle-Cazares *et al.*, 2010).

Most jurisdictions strictly regulate the environmental release of genetically engineered (GE) plants. In Canada, the release of so-called "plants with novel traits" (PNTs) is controlled by the Canadian Food Inspection Agency (CFIA, 2011a). As defined by the CFIA, "A PNT is a plant that contains a trait that is both new to the Canadian environment and has the potential to affect the specific use and safety of the plant with respect to the environment and human health. These traits can be introduced using biotechnology, mutagenesis, or conventional breeding techniques" (CFIA, 2011a).

Advanced technologies (including transgenesis) that produce PNTs offer major opportunities to increase productivity and efficiency, and to reduce resource consumption in agriculture (Beddington, 2010; Jaggard *et al.*, 2010). Significant volumes of research have been conducted to address the potential human health and environmental safety issues associated with the use of transgenic GE crops specifically.[34] Nevertheless, there are cases of public resistance to GE crops and foods. The development of PNTs, coupled with research on their safety and significance for the environment and health, are areas for continued research investment. Robust risk assessments (e.g., Parrott *et al.*, 2010) that also incorporate social acceptability issues for advanced technologies, including GE crops, are being considered in some jurisdictions so that environmental and food safety conditions and public concerns can be met (EC, 2010; Talas-**Oğraş**, 2011).

Nutrient Efficiency

Improved nutrient efficiency will become an increasingly urgent priority for maintaining yields, reducing fertilizer inputs as costs rise and environmental pressures increase, closing nutrient cycles, and mitigating problems and impacts associated with losses of agricultural nutrients to the environment. The harvest index (i.e., harvestable mass/total mass) of a crop is closely related to the efficiency of its use of nitrogen; therefore crop genotypes with a large harvest index are necessary to maximize nitrogen recovery (Ladha *et al.*, 2005). The genetic variation in harvest index indicates that the potential for further increases in nitrogen use efficiency is possible through plant selection (Ladha *et al.*, 2005). In contrast to drought tolerance, however, there is only limited success in developing commercial cultivars that use nutrients efficiently, due to poor understanding of "the genetics of plant responses to nutrients and plant interactions with environmental variables" (Fageria *et al.*, 2008). Overcoming these problems will require an approach that involves modern gene biotechnology and plant genomics, together with conventional plant breeding methods to develop nutrient efficient crop species, genotypes, and cultivars (Fageria *et al.*, 2008). Notwithstanding these potential difficulties, however, progress has occurred recently in the development of canola (*Brassica napus* L.) with improved nitrogen use efficiency, which is currently being evaluated in confined field trials by the agricultural biotechnology industry in Canada (CFIA, 2011b).

Synthetic Biology

Synthetic biology is defined as the design and construction of new biological parts, devices, and systems and the re-design of existing natural biological systems for useful purposes (RAE, 2009). It is an emerging technology that is expected to have wide-ranging implications for agriculture in the future (RAE, 2009). The agricultural technology sector anticipates that synthetic biology will lead to greater productivity, profitability, and sustainability by increasing, for example: crop water productivity; nitrogen use efficiency; yields; pest, disease, and drought resistance; and the quality, quantity, and processing characteristics of agricultural products

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[34] For instance, see EC, 2010.

(Dunbar, 2011). However, as with current methods of transgenic manipulation, concerns relating to the safety and health impacts of synthetic biology will need to be responsibly and carefully addressed (RAE, 2009).

5.7 TECHNOLOGIES TO SUPPORT PRECISION AGRICULTURE

Optimal resource utilization in agricultural systems, with minimal waste and pollution effects, needs to be undertaken in a systematic and integrated way, which depends on the accurate measurement of input and output parameters. Precision farming is a management system that, based on technology and data interpretation, promotes such environmental monitoring and control of agricultural practices (Roblin & Barrow, 2000). The objectives of precision farming are to: (a) describe the spatial distribution of factors affecting crop growth; (b) manage this spatial variability by applying variable-rate treatments of agrochemicals and fertilizers depending on location specific requirements; (c) maximize profitability; and (d) minimize environmental impacts (Roblin & Barrow, 2000).

The technologies currently available to farmers for precision farming include: GPS; field sensors (e.g., soil moisture); wireless environmental sensor networks for real-time decision making (Díaz *et al.*, 2011; Zerger *et al.*, 2010); variable rate applicators (VRA) for agrochemicals/pesticides, fertilizers, and solids (e.g., sewage sludge biosolids); yield monitors for harvestings; computer systems in cabs; accessible software systems for data collection storage and feedback control systems; remote sensing; soil sampling; and geographic information systems (GIS) (Roblin & Barrow, 2000). Welbaum *et al.* (2004) noted that combinations of these technologies enable a move away from “traditional inundative approaches” to agricultural management by providing “smart field” technologies. This requires real-time, computer-controlled electronic diagnostic devices to monitor soil and crop conditions, inform production interventions in an appropriate spatially focused and targeted manner, mitigate adverse environmental impacts of intensive agricultural practices, and lower per unit production costs (Welbaum *et al.*, 2004).

Measuring Spatial Variability of Field and Crop Parameters

Accurate, detailed information concerning the spatial variability of fields is a prerequisite for precision farming. This variability is affected by many factors, including crop yield, soil properties and nutrients, crop nutrient status, crop canopy volume and biomass, water content, and pests and diseases. However, a variety of sensors and equipment are available to measure these factors, including examples such as field-based electronic sensors, airborne spectral remote sensing, satellite imagery, and thermal imagery (Lee *et al.*, 2010). Sensing techniques for crop biomass detection, weed detection, soil properties, and nutrients are the most advanced of these technologies, and Lee *et al.* (2010) suggested that they have reached a sufficient level of development to be able to provide the data required for site-specific management. Nevertheless, further work is necessary to develop sensing technologies for remote and/or rapid measurements of soil conditions, particularly focusing on those that have a critical influence on root growth and, therefore, on crop productivity (Clark *et al.*, 2005).

Soil electrical conductivity (ECa) is one of the most frequently used measurements in precision agriculture. As outlined by Corwin and Lesch (2005a), this measurement provides information that "serves: (a) to characterize the spatial heterogeneity of several physico-chemical soil properties; (b) to identify the edaphic and anthropogenic factors that may influence crop yield; and (c) to provide a viable approach for delineating areas that behave similarly with respect to water flow and solute transport." Soil conductivity measurements provide a surrogate for deriving the spatial variability of a range of useful soil properties that may or may not influence crop yield. It is therefore necessary to calibrate the results with site-specific soil measurements to determine which factors are responsible for the ECa response to direct management actions. Sophisticated modelling tools are required for the comprehensive interpretation of the complex relationship between ECa and the geophysical environment (Pellerin & Wannamaker, 2005); however, practical protocols "to assure reliability, consistency, and compatibility of ECa survey measurements and their interpretation" are available (Corwin & Lesch, 2005b).

Infrared spectroscopic techniques also show potential to enable a quantitative evidence-based diagnostic surveillance approach to agricultural management systems (Shepherd & Walsh, 2007) and offer significant opportunities in the development of "on-the-go" sensing techniques. For example, based on a review of macro-nutrient assessment technologies, Sinfield *et al.* (2010) concluded that optical techniques (e.g., reflectance spectroscopy) showed the greatest promise for the development of an integrated sensor system for on-the-go detection of nitrogen, phosphorus, and potassium in soil. A new area of development for quantitative on-the-go soil analysis is the application of infrared photoacoustic spectroscopy, which offers several advantages over conventional reflectance spectroscopy, including simpler sample pretreatment and spectra recording, coupled with more useful data acquisition.

The direct measurement of crop water status using plant-based sensors has direct relevance to how plants are functioning, but it is dependent on the complex interaction between the plant and its sensor, and is therefore more difficult to interpret. Consequently, implementation at field scale has been limited by practical constraints (Jones, 2004; Lee *et al.*, 2010). One example of the direct monitoring of plant water status for irrigation scheduling is the use of acoustic emission (Jones, 2004).

Measuring the moisture content of the soil in which the crop is growing is one approach to determining the water supply. Significant progress has been made in the development of low-cost, low-power consumption, solar, and wireless soil water sensors, based on electromagnetic principles. These include time domain reflectometry and capacitance, deployed as direct measurement electrodes or porous-matrix sensors coupled to a dielectric device (Bogena *et al.*, 2007; Greenwood *et al.*, 2010; Sun *et al.*, 2009; Varble & Chávez, 2011). Consequently, the deployment of large numbers of probes to collect detailed spatial data will be possible in the near future, although the practicability of this and associated costs may ultimately favour rapid, non-contact detection and calibration with smaller numbers of field sensors.

Crop and soil water status can also be determined through remote sensing techniques. Significant progress has been made in the development of aerial, satellite, and hand-held remote sensing technologies, which are widely employed to measure the spectral responses of vegetation to physiological stress (Govender *et al.*, 2009). Measurements of surface temperature and reflectance (red and NIR spectrum) obtained through remote sensing can be used to determine water stress indices (Kustas *et al.*, 2003). An index, such as the Crop Water Stress Index (CWSI) (Jackson *et al.*, 1981), is used where there is full vegetation cover; for partially vegetated areas (such as during the early establishment stages of field crops), the Water Deficit Index (WDI) is used (Moran *et al.*, 1994). The CWSI, which provides a measure of the crop water status, and WDI, which can also be used to predict soil moisture and field water deficits, provide effective response triggers for irrigation schedule control. Therefore, remote sensing technologies based on infrared thermometry coupled to water stress models, offer significant potential opportunities to increase the efficiency of irrigation water use in different agricultural cropping systems (Alderfasi & Nielsen, 2001; Tanriverdi, 2010).

Weed and Disease Detection

Pesticide inputs to intensive agricultural systems can contaminate surface water and groundwater through runoff and leaching from treated sites. Various management strategies have been examined to mitigate these environmental impacts and the risks to public health that result from residual concentrations of pesticides detected in potable water supplies (Damalas & Eleftherohorinos, 2011; Fageria *et al.*, 2008; Reichenberger *et al.*, 2007). Principal developments in the application of precision agriculture techniques to pesticides have focused mainly on herbicide management with the objective of targeting herbicide treatments in the field to reduce inputs, environmental impacts, and cost (Weis *et al.*, 2008). Remote sensing techniques lack sufficient resolution to be an effective means of weed detection (Moran *et al.*, 1997). However, image-based identification and spectroscopic methods (for example, Blackshaw *et al.*, 1998; Chen *et al.*, 2002; Wang *et al.*, 2001) show potential for weed identification and threshold determination and have demonstrated the feasibility of automated weed control. Nevertheless, effective weed detection remains the primary barrier to automatic weed control systems, and research is required to improve sensor and application technologies (Slaughter *et al.*, 2008; Weis *et al.*, 2008).

Variable-Rate Application

Variable-rate application (VRA) is the final critical link in the chain of precision agriculture technologies. For a practical description of VRA techniques for precision agriculture, see Grisso *et al.*, 2011.

Site-Specific Management

Crop management interventions, involving pesticide, fertilizer, manure, and irrigation inputs can be targeted and applied with precision. To do so requires advanced application technologies that can achieve site-specific, automatic, pin-point delivery of variable optimum doses at specific field locations in real-time in response to remote and/or field sensing measurements of crop requirements, soil fertility, or weed cover.

Pesticides

Variable-rate application of pesticides is well established. Equipment that has been designed to perform this function with different degrees of automation can achieve the following objectives: flow-based VRA, map-based VRA, or sensor-based VRA (Grisso *et al.*, 2011). Automatic adjustment of the spray application rate to give the required volume of pesticide product per unit area independent of the forward ground speed of the equipment used to deliver the pesticide is widely practiced. In the U.K., for example, 59 per cent of the arable land area was treated with sprayers fitted with this type of basic variable rate system in 2004 (Garthwaite, 2004). Map-based VRA adjusts the concentration of the product being applied based on a predefined electronic (prescription) map linked to a GPS receiver to supply the desired rate as the applicator travels across the field (Grisso *et al.*, 2011). The use of sprayers linked to a GPS system accounted for 9 per cent of the treated total arable land area in the U.K. (Garthwaite, 2004). Sensor-based systems measure soil properties or crop characteristics using vehicle-based sensors on-the-go, and a control system uses this information to determine the required input to the location measured by the sensor (Grisso *et al.*, 2011). Variable-rate application of herbicides has developed to the greatest extent. Systems are available commercially, including sensor-based equipment; however, the deployment of advanced sensor-based applicators is still very limited. These technologies have significant potential to reduce pesticide inputs, one of the principal means of mitigating the impacts of pesticides through drainage and leaching pathways (Luck *et al.*, 2010; Reichenberger *et al.*, 2007).

Fertilizers and Organic Manures

Variable-rate fertilizer (VRF) application allows improved placement of fertilizer in root zones and better spatial matching of the rate of fertilizer application to crop requirements. VRF maintains maximum crop yields, reduces fertilizer and fuel consumption, and leads to significant environmental benefits from the reduced nutrient loadings and leaching losses (Galzki *et al.*, 2011; Schumann, 2010).

In contrast to VRF, VRA of solid and liquid manures, slurries, and biosolids is limited. However, equipment manufacturers offer automatic load cell and application rate control.[35] Funk and Robert (2003) describe the four levels of VRA control for liquid slurries, which are also applicable to solid manures: (a) manual flow rate control; (b) automatic flow rate control accounting for ground speed; (c) GPS/GIS mapped-based systems; and (d) on-board sensing of the product as it leaves the slurry tank (this helps with modulation of the application rate, since manure slurry is not consistent in terms of its nutrient content or fluid properties).

The cost of commercial VRA systems for manures is considered prohibitive. However, the availability of low cost GPS, control systems, and geo-reference mapping software may increase the viability of variable rate manure application (Dick *et al.*, 2010; Funk & Robert, 2003). In recent research for the Manitoba Livestock Manure Management Initiative,[36] Dick *et al.* (2010) showed that map-based VRF techniques can be adapted for manure applications through the use of conventional umbilical drag-hose. However, a number of practical issues limit the current wide-scale adoption of liquid manure by umbilical systems.

Prescriptive, fertility-based GIS maps and GPS control are also applicable to tanker and bulk spreader equipment, which have the advantage of automatic application rate control. Commercial systems are already successfully deployed, particularly within the agricultural contracting sector. However, obtaining representative nutrient content data is a limitation to all types of VRA technology for manures. Nevertheless, progress has been made in the development of on-the-go detection

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[35] For example, see http://www.gtbunning.co.uk/widebody_options.html).

[36] See http://www.manure.mb.ca/about-us.php.

techniques (e.g., NIR) that have the potential for real-time measurement and precision application of livestock slurry (Saeys *et al.*, 2004). Rapid, on-farm tests are also available for measuring manure nutrient composition and properties that could be used to inform prescriptive application rates for VRA of manures, although they tend to be more effective with liquid compared to solid manure types (Singh & Bicudo, 2005; Van Kessel *et al.*, 1999). To overcome the other potential limitations of umbilical application systems, Dick *et al.* (2010) suggested that the benefits of precision farming techniques could be realized on manured land by applying a base rate of liquid manure using traditional methods in conjunction with precision, site-specific VRF application technologies to balance and optimize the overall inputs of crop nutrients.

Irrigation

In contrast to precision application of pesticides and fertilizers, variable-rate irrigation capable of managing irrigation spatially is a relatively recent development. The quantitative benefits of variable-rate irrigation are attributed to a number of factors, including: prevention of irrigation to uncropped areas; reduced irrigation amounts to avoid oversupply (e.g., depending on site topography); and optimized irrigation to adapt to spatial productivity (Sadler *et al.*, 2005). The average water savings by precision irrigation were 10 to 15 per cent compared to conventional irrigation practices, and could be as high as 50 per cent, depending on the efficiency of the previous irrigation management regime. Additional reported benefits include: increased harvestable area; decreased incidence of disease; and reduced leaching or risk of leaching nitrates (Sadler *et al.*, 2005). The latter reduces losses of valuable fertilizer nutrients, maximizes potential retention and utilization of nutrients in the crop root zone; and reduces environmental nutrient emissions and impacts. The priorities for future research to increase the utility of precision irrigation include improved real-time monitoring technologies and decision support systems (Sadler *et al.*, 2005).

Robotics and Software

Agricultural robotics is a rapidly developing area and may be predicted to have an increasingly important contribution to agricultural production systems in the relatively near future. One of the key benefits of an autonomous systems approach in agriculture will be to increase the overall efficiency and precision of farming operations to optimize crop production by managing interventions and inputs of irrigation, pesticides, and nutrients at the correct rate and time in relation to the stage of crop development and spatial, environmental, and soil factors (Bak & Jakobsen, 2004; Blackmore *et al.*, 2005). Together, these advances will lead to increased agricultural production while reducing inputs, wastage, and subsequent impacts on the environment, thus improving the overall sustainability of modern agricultural systems (Cariou *et al.*, 2009; Lopes & Neto, 2010). Based on a systems analysis and economic feasibility study, Pedersen *et al.* (2005) also showed that autonomous robotic vehicles were consistently more economically viable than conventional methods of agricultural mechanization. However, significant challenges remain and current research is leading to the development of autonomous vehicles that will enable precision control of machinery and functionality over terrain with variable surface characteristics over the annual production cycle (Bak & Jakobsen, 2004; Cariou *et al.*, 2009). To realize the full benefit that autonomous systems can offer will require a strategy promoting strong interdisciplinary research to integrate expertise in the areas of field application systems, and field-based and remote sensing technologies coupled with advanced software development to interpret input monitoring data to simulate and control agricultural processes (Lopes & Neto, 2010).

5.8 FERTILIZER AND PESTICIDE FORMULATION

Controlled-release fertilizers can improve the efficiency of nitrogen use by matching nutrient release more closely to crop demand compared to conventional soluble mineral fertilizers. Many different formulations are available (Ladha *et al.*, 2005). However, while the use of controlled-release fertilizers has doubled in recent years, they account for less than 0.2 per cent of the total fertilizer nitrogen applied due to their high cost, which can be 3 to 10 times that of conventional fertilizers (Ladha *et al.*, 2005). Application of nitrification inhibitors with ammonium-N-based fertilizers is another approach to increase nitrogen use efficiency and crop yield; 9 per cent of maize growers in the U.S. supply nitrogen fertilizer with nitrification inhibitors (Ladha *et al.*, 2005).

Government and environmental regulators are demanding improved formulations of pesticides that are safer, have minimal impact on the environment, and can be applied at low dose rates (see Box 5.1). The agrochemical industry is responding by developing enhanced pesticide formulations to improve environmental safety (Knowles, 2006, 2008). Formulation technology is focused on improving operator safety, optimizing the biological activity of the pesticide to reduce the dose rate and waste of pesticides applied to crops, and reducing environmental impact and increasing food safety. The development of new pesticides with novel modes of action and enhanced safety profiles, such as those based on natural products (e.g., microbial-based biopesticides) (Arias-Estévez *et al.*, 2008; Damalas & Eleftherohorinos, 2011; Montesinos, 2003), and soluble fermented compost extracts (Scheuerell & Mahaffee, 2002), as well as improved formulations of pesticides already used by farmers, are suggested methods to reduce the potentially adverse effects of pesticides on the environment (Damalas & Eleftherohorinos, 2011). Synthetic biology techniques will also be developed in future to engineer pesticides that have specific targets and modes of action coupled with biodegradable environmental residues (RAE, 2009).

Box 5.1
Pesticide Formulation and Water Protection in Canada

Pesticides can require 10 years or more of scientific research, development, and government evaluation to gain registration (Health Canada, 2011a). These research studies are conducted both in the laboratory and the field to demonstrate that pesticides pose a reasonable certainty of no harm to the environment including all living organisms, air, land, and water (Minister of Justice, 2002). For water protection, the answers to a number of primary questions are sought during research and development for registration: How does the pesticide degrade? What are the breakdown products? How persistent is it in the environment? Does it bio-accumulate? How mobile is the pesticide in soil? If it reaches water ecosystems, how does it affect the health of aquatic organisms? To answer these questions, specific studies are undertaken to determine the pesticide's physical and chemical properties; transformation processes including degradation by light, chemical, and biological means; and mobility. These environmental fate data are then used with environmental toxicology studies that analyze the effects of pesticides and their major metabolites on non-target aquatic organisms including fish and algae to determine environmental risk (Health Canada, 2004; Whitford *et al.*, 2001). Pesticides are also subject to continued monitoring and re-evaluation, taking into account the latest scientific standards and developments (Health Canada, 2009b, 2011b), although, as noted in Chapter 3, there are a number of issues concerning lack of appropriate standards for individual pesticides and mixtures of pesticides in the water environment.

There have also been many advances in pesticides and pesticide use technology that have resulted in improved water protection (Knowles, 2008; Ozkan, 2009). Many new reduced risk pesticides have been registered with characteristics such as low impact on human health, lower toxicity to non-target organisms (birds, fish, plants), low use rates, and low potential for groundwater contamination (U.S. EPA, 2012). Advanced pesticide formulations have reduced application rates, eliminated volatile solvents, and included bio-enhancements that offer better plant tissue adhesion and increased uptake and translocation in the plant (Knowles, 2008). New pesticide application technologies have also been developed such as low drift nozzles and

continued on next page

variable rate applicators that use GPS and photo sensors to target only pests and severe infestations (Ozkan, 2009). Pesticides are also increasingly being applied at seeding as seed treatment formulations. Seed treatments have allowed greater targeted pesticide delivery to protect the seed and developing plant tissue directly, thus reducing the need for multiple applications (Knowles, 2008).

The agriculture industry has also embraced Integrated Pest Management (IPM) and other BMPs. IPM is the process where pest population damage thresholds, pest biology, and alternative pest management techniques are considered with pesticide application in a holistic manner (Maredia *et al.*, 2003). Agricultural BMPs such as conservation tillage and buffer strips can reduce runoff and erosion and protect surface water (Hilliard & Reedyk, 2000). In addition, The Food System 2002 Program in Ontario showed that reduced pesticide use could be achieved through education of farmers and targeted research without negatively affecting crop yields (Gallivan *et al.*, 2001). Together these practices have undoubtedly resulted in better pest management, improved environmental stewardship, and increased water protection than was possible with previous chemicals and practices.

5.9 PLANT GROWTH REGULATORS AND OSMOLYTES

An alternative approach to plant breeding and genetic manipulation to improve crop drought tolerance is the exogenous application of chemical biostimulants, including organic compounds (organic osmolytes and plant growth regulators) and mineral nutrients (Ashraf *et al.*, 2011). This strategy has gained considerable attention recently because of its efficiency, feasibility, and cost- and labour-effectiveness. Microbiological treatments (e.g., H_2-oxidizing bacteria) that show plant-growth-promoting properties, including the inhibition of ethylene biosynthesis that enhances root elongation and plant productivity, may also provide promising biofertilizers if they can be successfully formulated (e.g., as seed inoculants) (Golding & Dong, 2010). Use of plant growth regulators to manipulate plant architecture and flowering is well established in commercial horticultural practice. This experience demonstrates the effectiveness that such biostimulants may have on plant development and physiological responses. However, the modes of action and delivery mechanisms required for drought tolerance manipulation and biofertilization are poorly understood, but the prospects are that research in these areas would yield significant benefits to agricultural production in the short to medium term (Ashraf *et al.*, 2011).

5.10 SOIL STABILIZERS

Polyacrylamides are used internationally and in Canada for a wide range of industrial purposes, including as flocculants in water and wastewater treatment, and they are also used for soil erosion prevention (Environment Canada & Health Canada, 2009). Polyacrylamide-containing soil amendments must be registered as supplements under the *Fertilizers Act* and the percentage of acrylamide monomer specified (CFIA, 1997). Anionic polyacrylamide (PAM) has been used extensively since 1995 to reduce irrigation-induced soil erosion and enhance infiltration. The properties, benefits, and utilization of PAM in agricultural land management were recently reviewed by Sojka *et al.* (2007). The soil stabilizing and flocculating properties of PAM are reported to significantly improve runoff water quality by reducing suspended solids, nitrogen, dissolved reactive and total phosphorus, COD, pesticides, weed seeds, and microorganisms (e.g., pathogens) in runoff. Sojka *et al.* (2007) concluded that modified water management with PAM has great promise for water conservation and would contribute to reducing agricultural impacts on ecosystem services. The effectiveness and low cost of PAM, coupled with the practicability of its use, explain the rapid adoption of the technology in the U.S. where an estimated 800,000 ha of irrigated farmland receive PAM for erosion and/or infiltration management.

The benefits of PAM for agricultural production and improving surface water quality in agricultural catchments are well documented. However, while there is no evidence of negative effects of PAM on soil ecological systems or the environment, a potential disadvantage is that PAM degradation occurs slowly in soil, at a rate of 10 per cent per year (Sojka *et al.*, 2007). In future, biopolymers that degrade more rapidly are likely to gain greater acceptance, and further research to develop alternative soil stabilizers is justified (Orts *et al.*, 2007). This may also be driven by the increasing energy costs associated with PAM production (Orts *et al.*, 2007).

5.11 NANOTECHNOLOGIES

Nanotechnology applications are being developed for different agricultural uses including: the detection of pathogenic and parasitic organisms; sensing of environmental conditions and properties (such as humidity, soil moisture, and soil and groundwater contaminants); the controlled release of fertilizers and pesticides; improved water retention in soils and uptake by plants; drug delivery and improved nutrient utilization in livestock; degradation of organic contaminants; and water treatment (Kabiri *et al.*, 2011; Knauer & Bucheli, 2009; Manimegalai *et al.*, 2011; Thornton, 2010). Wireless nanosensors, for example, can be used in combination with remote sensing and precision irrigation systems to greatly enhance WUE.

Nanoscale technologies for fertilizer and pesticide application can greatly reduce runoff and water contamination. Most nanotechnologies are still in their infancy, and associated risks and benefits must be carefully evaluated. Nonetheless, they represent a promising approach towards greater improvements in WUE (OECD, 2010). However, the potential for negative impacts of nanotechnologies on the environment and health needs to be researched (Knauer & Bucheli, 2009) and their application supported by risk assessment.

5.12 LIVESTOCK TECHNOLOGIES

Industrialization of livestock production can lead to increased air and water pollution. However, developments in breeding, nutrition, and animal health will continue to increase potential production, efficiency, and genetic gains, and contribute to mitigating environmental impacts (Thornton, 2010). For example, in developed regions, livestock breeding will continue to focus on productivity, but will also improve animal welfare and disease resistance (to reduce reliance on pharmaceuticals and antibiotics), and reduce environmental impact (such as methane production) (Thornton, 2010). As in the case of plant breeding, the field of molecular genetics is likely to have a profound impact on livestock improvement, and it is anticipated that genomic selection may be able to more than double the rate of genetic gain in the dairy industry for instance. The complexity of the impacts of breeding to increase efficiency of resource utilization, and the associated influence on other characteristics, including animal fertility and environmental impacts (e.g., methane), will require whole-system assessments, using life-cycle analysis techniques, to determine the balance of the costs and benefits (Hayes *et al.*, 2009; Thornton, 2010). Further research is required to improve animal feed conversion efficiencies, which would also provide an important contribution to better overall water productivity of feed/fodder-animal production systems (Peden *et al.*, 2007).

Factors identified for improving global livestock water productivity include: (1) increasing the use of crop residues and by-products; (2) grazing on well-managed rangelands unsuitable for crop production; (3) managing the distribution of feed resources to better match availability with demand; (4) adopting water conservation management practices; and (5) selecting animals adapted to dryland conditions (Peden *et al.*, 2007). Improved feeding practices, such as increasing the amounts of concentrates or improved pasture quality, can reduce methane production; emissions may also be reduced through various dietary additives. However, their effectiveness and viability at greenhouse gas mitigation require further research. Significant opportunities exist to improve the water productivity associated with livestock production, however, in contrast to the extensive body of information available on crop-water relations, much more research and knowledge on livestock-water interactions is required (Peden *et al.*, 2007).

Review of Key Findings

- Developments in agricultural technologies are advancing rapidly and will be essential to deliver the future expectations of agriculture in terms of increasing productivity, while at the same time adopting a more conservation-based, ecosystems sensitive approach, and adapting to increased competition for water resources in the short to medium term, and climate change in the longer term.
- Priority areas for research include: improving crop and livestock water and nutrient productivity and disease resistance; an interdisciplinary approach to precision and smart agricultural systems, including robotics, and related field based sensor, modelling, and software development; nanotechnologies; pesticide and fertilizer formulation; fluid biomulches, and low-cost treatment technologies to protect water ecosystems. The focus should be directed towards those technologies that can provide the greatest contributions to improving water productivity, mitigating environment impacts, and enhancing the overall productivity and resiliency of agricultural production.
- In addition to these fundamental research needs, farm-scale demonstration programs would be an effective way to demonstrate the benefits and practical application of emerging technologies that are at a “near market” stage of development, and ready for wider, full-scale deployment, to increase their uptake.
- Extension services to provide information and advice to farmers on new technologies are also necessary for the effective deployment and adoption of research and technology developments.
- There would be advantages in drawing together and reviewing the research information and experience available in Canada on irrigation systems and management, harvesting rainwater and blowing snow, and constructed wetlands design and operation (particularly in relation to cold weather performance and for providing an irrigation water resource), so as to develop or revise best practice guidance for the implementation and/or improved operation of these technologies.

6

Building the Foundation for Sustainable Management of Water in Agriculture

- The Changing Context for Governance and Management of Water in Canada
- Economic Instruments to Support Sustainable Water Management
- Knowledge Transfer and Stakeholder Engagement Strategies
- Employing Effective Governance and Policy Tools to Support Sustainable Management of Water for Agriculture

6 Building the Foundation for Sustainable Management of Water in Agriculture

Overview

Water management decisions to promote sustainability must consider the economic, environmental, and social value of water. Adopting appropriate governance structures, valuation techniques, economic incentives, and knowledge transfer strategies that consider these values is essential to the achievement of sustainable water use in agriculture. Further research in these areas is needed to facilitate better management decisions, improve uptake of sustainable practices, and enable the agricultural community to build closer working relationships with other sectors and stakeholders to resolve cross-sectoral challenges.

Sustainable water management for agriculture requires satisfying the needs of current stakeholders, as well as the environment, while simultaneously managing the resource in ways that preserve its availability for future generations. Previous chapters examined practices and technologies that are known to contribute to sustainable water management. In this chapter, the focus is on the foundation that is needed to implement those practices. The Panel believes this foundation is based on effective governance, together with the use of appropriate economic instruments and knowledge transfer strategies that support the adoption of behaviours at the individual, community, and sector levels that contribute to sustainable agricultural water management.

6.1 THE CHANGING CONTEXT FOR GOVERNANCE AND MANAGEMENT OF WATER IN CANADA

The term *governance* refers to the ways in which societies organize themselves to make decisions and take actions in a context such as water management (Folke *et al.*, 2005). Of particular concern are the ways in which decisions are made, the people and organizations who are involved in making those decisions, and the roles they play. Contemporary water governance processes in Canada are diverse and include traditional regulatory approaches, collaborative processes, market-based processes — and combinations of all of these (de Loë & Kreutzwiser, 2007; Hill *et al.*, 2008). This section provides a brief overview of the key actors and institutions for water governance in Canada (emphasizing those pertinent to agriculture).[37] Following this brief overview, key principles and practices that can provide a stronger foundation for governance are discussed.

The Organization of Governance for Water in Canada

Historically, water governance in Canada has occurred in a top-down fashion, with government agencies playing leadership roles, and being accountable for their decisions (de Loë & Kreutzwiser, 2007). Contemporary water governance in Canada is building on this foundation. The constitutionally-defined responsibilities of the federal and provincial governments have not changed; therefore, these levels of government are and will remain central actors in governance for water. However, governance increasingly also involves the use of markets and other economic instruments, voluntary codes of practice, partnerships, multi-stakeholder councils, and various forms of shared and collaborative planning and decision-making. The result is that responsibility for water-related governance functions is now divided among a host of government and non-government actors, including private industry and industry groups, Indigenous peoples, the public sector, non-governmental organizations, and individual concerned citizens. Because of these changes, governance for water in Canada is considerably more complex today than it was in previous generations. Consequently, a host of new challenges exist relating to effectiveness, capacity, legitimacy, and accountability. As understanding of how best to address these is uneven, this represents an important area for future research.

The Canadian Constitution provides the basic foundation for water governance in Canada. It assigns authority to the federal government and the provinces (Saunders & Wenig, 2007). This authority is shared, which contributes to what analysts describe as a highly fragmented system (e.g., Bakker & Cook, 2011). Water bodies that fall solely within provinces are the constitutional responsibility of provinces. Key areas of provincial responsibility include flow regulation, water allocations, pollution control, and thermal and hydroelectric power development (Environment Canada, 2011c). Not surprisingly, there is enormous variation from province to province in how water is governed. For example, in the case of water allocation, a prior allocation system is used in the province of Alberta. Water allocation is based on licences, with senior (older) licencees having priority over junior licencees. As discussed later in this chapter, licence holders in Alberta are legally permitted to transfer their allocations through market mechanisms (Alberta Environment, 2003). In contrast, in Ontario, those wishing to take more

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[37] Little agriculture occurs in northern Canada, where water governance is quite different than in the provinces. Thus, the material presented here does not address governance in Canada's territories.

than 50,000 litres of water per day must acquire a permit from the provincial government. There is no priority among permit holders. Therefore, during times of shortage, the provincial government attempts to ensure equity among users (Ontario Ministry of the Environment, 2005). For agricultural water users, the result is widely varying security of access to water depending on the province in which they are located (de Loë *et al.*, 2009).

Canada's federal government has a series of critical powers under the Constitution, but these are more narrowly defined than those of the provinces. Federal authority relates to specific concerns such as national parks, First Nations reserves, and other federal lands; fish and fish habitat; navigable waters; and waters that flow across provincial/territorial boundaries and the international boundary between Canada and the U.S. Within the federal government, over 20 departments and agencies have responsibilities for fresh water (Environment Canada, 2012b).

Numerous other actors also play key roles in governance for water in Canada. As noted previously, First Nations peoples in Canada are the fiduciary responsibility of the federal government under Canada's Constitution. However, as Phare (2009) notes, due to land claims and self-government agreements and treaties, the entrenchment of Aboriginal rights in the Constitution, and ongoing affirmation of Aboriginal rights by the Supreme Court of Canada, Aboriginal peoples in Canada have unique rights — as governments and as individual rights-holders — to be active participants in decision-making related to water.

The Constitution does not assign specific responsibilities for water to municipalities. However, they have been assigned key responsibilities for drinking water provision and land use planning under the authority of provincial statutes. Municipalities are also responsible for regularly sampling, testing, and analyzing water to ensure that it is safe and meets provincial standards (McFarlane & Nilsen, 2003). Municipalities are also involved in numerous collaborative monitoring programs with industries, public and farm organizations, and universities. The benefits of these programs consist of sharing the costs and more efficient use of the data gathered (Harker *et al.*, 2000).

In basins shared with the United States, the bi-national International Joint Commission formed under the *Boundary Waters Treaty of 1909* serves to prevent and resolve disputes related to water sources shared by the two countries (Findlay & Telford, 2006). Shared water basins are found across the country, from the international Abbotsford-Sumas aquifer in the west, to the Saint John River Basin in the east. Farmers in these basins and aquifers are affected by the decisions made by the two countries. For example, the amount of water available to irrigated agriculture in southern Alberta's Oldman River Basin is determined in part by an order of the International Joint Commission in 1921 (Halliday & Faveri, 2007).

Through a growing shift to sharing of responsibilities with actors outside of governments, citizens, non-government organizations (NGOs), and private firms have emerged as key actors in governance for water. For example, during the last 30 years, NGOs have been taking on a larger role in water governance in Canada. This includes participation in consultations, public education, information exchange, and research. By generating public interest in water issues, NGOs also have an important influence on public debate on water policy issues (Bakker & Cook, 2011).

Finally, multi-stakeholder organizations — some created by governments, and some that formed independently at the grassroots level — are also playing key roles in planning, and sometimes policy making, for water (see Box 6.1). These organizations may make decisions and take actions that affect the agricultural sector. Therefore, farmers are strongly motivated to participate in their activities (Murray & de Loë, 2012). For example, in 2000, following the contamination of the water supply in Walkerton, Ontario, source protection committees were formed in Ontario to create detailed plans at the watershed scale that identify threats to drinking water supplies and define specific measures to address those threats. Many of the threats identified through this process are found on agricultural land and originate from common farm practices (Ontario, 2009). Therefore, in recognition of the fact that the plans created by these committees will directly affect producers, one-third of their members must be people who represent agricultural, commercial, or industrial sectors of the economy in the region in which the committee has jurisdiction (Ontario, n.d.).

Fragmented jurisdiction over water in Canada is often cited as a challenge for water governance and management (Bakker & Cook, 2011; Hoover *et al.*, 2007; McFarlane & Nilsen, 2003). With many levels of government and a host of non-government stakeholders involved, there is a heightened need for coordination and collaboration to ensure that roles and responsibilities are well defined, issues that cross boundaries and jurisdictions are addressed, and that the sustainability of water resources is ensured (Bakker & Cook, 2011; Hoover *et al.*, 2007). Recognizing this need, the last five years have seen growing calls for increased coordination and rationalization of governance for water in Canada from organizations such as the Gordon Water Group (Morris *et al.*, 2007), Pollution Probe (2007), and the Canadian Water Resources Association (de Loë, 2008). The focus of these reports is water governance and management, broadly. Nonetheless, they each clearly demonstrate a range of challenges for the agricultural sector from the current

Box 6.1
Quebec's Watershed Organizations

In 2002 the Quebec government enacted a new water policy that included integrated watershed management (Ministère du Développement durable, Environnement et Parcs, 2002). This approach uses non-profit watershed groups that consist of public and private stakeholders, including farmers, and representatives from relevant NGOs. Governments have representative members in these watershed groups, but they do not have a vote (Robins, 2007). The Quebec water policy requires that these organizations have balanced representation to ensure all relevant stakeholders have a voice in the decisions (Nowlan & Bakker, 2010). The groups develop a Master Water Plan for their watershed that is then approved by the province (Ministère du Développement durable, Environnement et Parcs, 2002). The individual watershed groups throughout the province depend on the "regroupement des organisations de bassin versant du Québec" (ROBVQ) for support and to represent them in forums with governments (Robins, 2007). The ROBVQ also promotes the exchange of information between watershed organizations and develops and distributes tools for training, monitoring, and governance (Robins, 2007).

uncoordinated, fragmented approach, while simultaneously highlighting ways in which the agricultural sector would benefit from a more coordinated approach to governance for water. Clarifying the implications for agriculture that result from this fragmented approach, and identifying ways of addressing those concerns, is an important research priority.

Principles for Effective Governance

Many jurisdictions are grappling with the effort to develop more effective governance frameworks for sustainable management of water resources. As outlined in reports by the World Water Council and others, effective governance is essential to support the use of technical innovations and BMPs (Cosgrove & Rijsberman, 2000b; Tropp, 2007). Without effective governance, there is only so much that can be achieved through technology and BMPs. Though no single "one-size-fits-all" framework can be right for all jurisdictions (given differences in legal regimes, institutional settings, and socio-economic contexts) (Tropp, 2007), the Panel believes there are several principles that have been shown to be effective in supporting sustainable management of water resources for agriculture and other human and environmental purposes.

Ensuring Water Governance Operates at the Appropriate Scale

The appropriate scale for water governance varies depending on context. For many water problems relevant to agriculture, the local scale is important. As discussed in previous chapters, water resources frequently do not follow the same boundaries as municipalities, counties, provinces, or even national governments, and there can be many levels of government and stakeholders with various responsibilities and interests relating to a given water resource. This means that decisions and actions for one level or location can affect others. There is broad recognition that watersheds can provide a focus for coordinating decisions and actions (Nowlan & Bakker, 2010; NRTEE, 2010a). It makes little sense, for example, to engage in efforts to clean up water quality downstream without the cooperation of partners upstream, as upstream pollution may defeat the efforts of those situated downstream. Similarly, monitoring withdrawals in only one part of a watershed may not be appropriate if changes in water flows in other parts of the hydrological system can also have a major impact on water quantity in an area being monitored.

Managing water resources at the appropriate scale allows for the integration of management efforts and knowledge, supporting more effective governance of water resources (NRTEE, 2010a). In recent years there has been a shift towards governance that takes into account local concerns and the role of watersheds. Examples include Quebec's Watershed Organizations and Ontario's Source Protection Committees. However, long-standing watershed-based approaches to engaging local stakeholders predate these initiatives. Perhaps the best example is Ontario's locally-organized conservation authorities (CAs). The 1946 *Conservation Authorities Act* provided the means by which CAs could be created. Since 1946, 36 Conservation Authorities have been established in Ontario to manage water and other natural resources on a watershed basis. CAs are based on partnerships with municipalities, which provide the members of their boards (Mitchell & Shrubsole, 1992). The operating budgets of CAs are, on average, supplied by self-generated revenues (42 per cent), municipal levies (33 per cent), provincial grants and special projects (23 per cent), and federal grants or contracts (2 per cent) (Conservation Ontario, 2011). A total of 90 per cent of the population of Ontario lives in a watershed that is managed by a CA. Overall, CAs in Ontario have been very successful at working with municipal, provincial, and federal governments to yield community-based solutions to natural resource problems (Conservation Ontario, 2011).

More importantly, the role watersheds (and other natural boundaries) should play in *governance* (as opposed to *management*) is also context-dependent. For example, the water governance literature recognizes that watersheds play a critical role in identifying key links and relationships among water and land, and help to define the people and communities who share a common interest by virtue of occupying the same watershed. However, this literature increasingly argues that organizing governance based on watershed boundaries is problematic (e.g., Cohen & Davidson, 2011). For instance, choosing which of the many possible watershed boundaries to use is often a political rather than a scientific decision. More pragmatically, the organizations that have the political legitimacy to make decisions, and to be accountable for their decisions (e.g., provinces, municipalities) do not have boundaries that align with watersheds (Cohen & Davidson, 2011). In the context of agriculture, a further problem is the fact that it cannot be assumed that farmers relate to the watershed (a hydrologic unit). To illustrate, a study of the role of watersheds in Ontario's farm sector found that farmers relate to their local county rather than their local watershed (Ferreyra *et al.*, 2008). Thus, in considering the most appropriate scale for governance, care is needed to ensure that the scale chosen is relevant and appropriate for the needs of the agricultural sector.

Integrating Land-use Planning with Water Management Decisions

A consensus is emerging in the literature and among practitioners regarding the need to integrate land use planning with water management decisions at the appropriate unit of water management and analysis (e.g., watershed, river basin, or aquifer) (see, for example, de Groot *et al.*, 2010; Millenium Ecosystem Assessment, 2005). Land use and water management are closely interrelated. The use of land for agriculture, for instance, can affect water quantity (e.g., through water withdrawals for irrigation) and water quality (e.g., through runoff of fertilizers or pesticides) in a given watershed (see Figure 6.1). The same is true of other land use and management decisions, including the development of golf courses, hydroelectric dams, or suburban residential areas. There are also environmental, aesthetic, and cultural considerations to be taken into account, as the combined impact of land use and water management decisions can affect wildlife habitats, flood risk potential, and many other characteristics of the local landscape and ecosystems. At the same time, these land and water uses provide certain benefits for local communities, including food, recreational opportunities, electrical power, and employment. Integrating land use and water management decisions can help to maximize the outcomes for the greatest number of stakeholders, while minimizing the impact of the decisions on the environment, economy, and society.

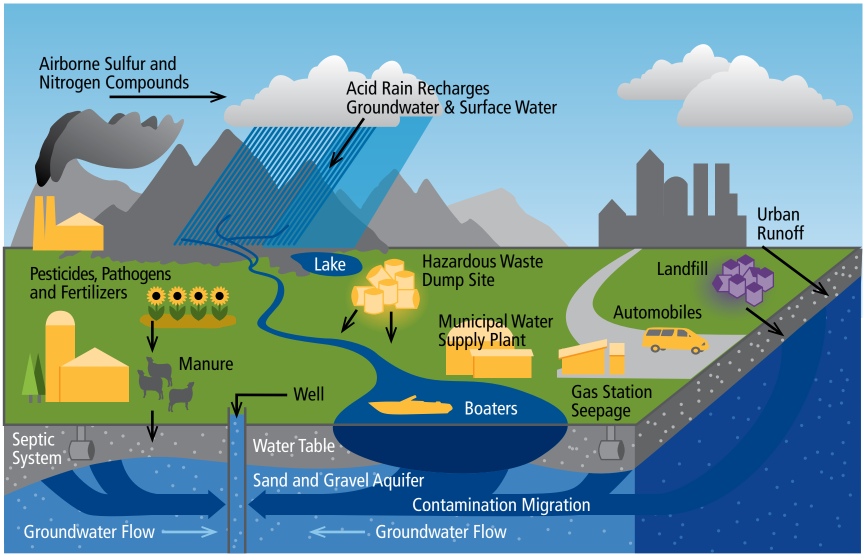

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Figure 6.1
Human Activities Affecting Source Water

Unfortunately, the track record of actually integrating land and water on the ground is mixed. Many of the challenges relate to the complexity and fragmentation described in the previous sub-section. Simply put, there are so many interconnections (see Figure 6.1) that the number of actors involved will always be high, and these actors will have different mandates, jurisdictions, and interests. As a result, there is a growing consensus in the literature that simplistic efforts to accomplish integration by creating special purpose organizations, or through layering on additional requirements for integration, are inappropriate (e.g., Cervoni *et al.*, 2008). Instead, researchers are reframing the problem as one of coordination and collaboration. For instance, Fish *et al.* (2010) stress the need for collaborative approaches that can cope with the interactions and uncertainty that are characteristic of contemporary water management. Plummer *et al.* (2011), in an evaluation of land use planning and watershed management in Ontario, demonstrated that integration can be accomplished through better recognition of links and relationships among planning instruments.

Involving Affected Stakeholders in the Decision-Making Process

Water management decisions can affect the lives of people living within watersheds in a myriad of ways, influencing everything from the industries that can be established to environmental conditions to recreational possibilities. Because water management decisions may also involve trade-offs among these and other competing uses, it is important not only to integrate the views and concerns of the relevant stakeholders who may be affected by such decisions, but also to involve affected stakeholders in decision-making. Experiences from around the world suggest there are three main benefits that can be achieved by adopting such an approach (Ansell & Gash, 2008; Reed, 2008). First, decisions that involve collaboration and participation are more likely to be seen as having legitimacy in the local community. Second, the legitimacy offered by collaborative approaches to decision-making can improve stakeholder buy-in, potentially leading to community support for policy implementation. Third, involvement of relevant stakeholders in decision-making can enhance policy- and decision-maker access to important information, whether in the form of stakeholder preferences or practical knowledge about the nature of a given watershed and landscape.

The precise forms of collaboration and the tools for incorporating participation will vary according to local circumstances and the types of decisions to be made. Hence, numerous formal and informal processes for engaging citizens in governance relating to water exist in Canada. These include standard public notification, consultation, and appeals provisions in the legal frameworks for water management in each province. Elections are another vehicle through which citizens can express their views to elected officials. From the viewpoint of governance, the collaborative processes that are becoming more commonplace in Canada and around the world are an important and relatively new trend. As noted previously, these processes are shifting public engagement from simple consultation to limited roles in decision-making and plan implementation. Examples include Quebec's Watershed Organizations and Ontario's Source Protection Committees. Numerous other formal and informal examples currently exist in Canada (e.g., Low Water Response Teams in Ontario; Watershed Planning and Advisory Committees in Alberta) (de Loë & Kreutzwiser, 2007; Nowlan & Bakker, 2010). Given the importance of water for agriculture and the extensive nature of farming in Canada, it is essential that farmers, individually and collectively, become skilled at participating in these processes.

Incorporating Knowledge into the Decision-Making Process

Effective decision-making in relation to water resources requires the incorporation of scientific and other forms of knowledge. As discussed throughout this report, scientific data and analysis can provide insight into changes in water availability and quality, the efficacy of BMPs, and many other considerations for water management decisions. Economic valuation tools are another important source of information needed to inform decision-making. Science can be employed as a tool for informing these decisions, and for helping stakeholders understand the real trade-offs, costs, and benefits of various management strategies, as well as the costs of doing nothing (CCA, 2009; NAS, 2009). To be an effective tool, however, scientific input needs to be grounded in strong data and analysis. In addition, scientific input has to be viewed as relevant by decision-makers, giving an appropriate level of consideration to the full range of uncertainties and the potential risk scenarios involved in any decision.

In addition to scientific knowledge, effective water management and governance requires insights derived from applied expertise, traditional knowledge, and local knowledge (NAS, 2004b; Tress *et al.*, 2006). Integration of scientific and other forms of knowledge in decision-making processes can lead to more robust solutions that account more effectively for the complex and interconnected nature of current water management and governance challenges (Raymond *et al.*, 2010). Numerous barriers exist to integrating different forms of knowledge. Knowledge "co-production" models are often advanced as a way to place different knowledge contributors on a level playing field (Corburn, 2003).

Transdisciplinary research is one way to facilitate knowledge co-production. In transdisciplinary research, researchers and community members are equal partners in defining problems and approaches to addressing those problems (Tress *et al.*, 2006). This type of research can also help clarify the costs and benefits of various forms of land use, land management, and water management decisions, as well as how decisions in any one of these areas may affect the others. This allows for a clearer picture of the trade-offs involved and the distribution of costs and benefits. Tools such as scenario analysis and multiple criteria decision analysis can be employed to support decision-making as well, while economic and communications tools can be used to promote sustainable choices and management practices. Land and water management in the Oldman River Basin provides one example of the benefits that can be derived when several of these tools are used in concert, leading to better-informed, higher quality decisions (see Box 6.2).

Box 6.2
Science Supporting Decisions in the Oldman River Basin

The Oldman River Basin covers approximately three million hectares in Alberta's south, where over 160,000 people live, with almost half residing in Lethbridge (Koning *et al*., 2006). There is a wide range of vegetation in the basin, from coniferous forest to native prairie and grasslands. There is also significant agricultural activity in the basin with 57 per cent of the land used for farming, the majority of it devoted to canola and cereal (Oldman Watershed Council, 2005).

In 1997, concerns over deterioration of water quality led to the formation of the Oldman River Basin Water Quality Initiative (OMRBWQI). At the time, limited factual information was available and there was a tendency towards finger pointing about possible contamination from agricultural expansion and urban activities (Koning *et al*., 2006). The goals of the OMRBWQI were to document the quality of the surface water in the region, examine the relationship between land-use and water quality, and identify areas of concern. Through scientific analysis, the initiative sought to determine whether the concerns of residents were valid and where improvements should be made.

In the first five years, the OMRBWQI collected water samples at 108 locations on a bi-weekly to monthly basis. The samples were analyzed by trained government staff for a variety of contaminants including nutrients, dissolved sediments, pesticides, fecal coliform bacteria, and *E. coli* (Koning *et al*., 2006). River flow data were taken from permanent gauged sites monitored by Alberta Environment and the Water Survey of Canada. Alberta Environment, along with Environment Canada, also provided meteorological data. The information from smaller inflows was collected by field staff taking on-site flow measurements.

The data collected demonstrated that, in general, the water quality in the river was good and almost always better than the guidelines set by the governments of Canada and Alberta (Oldman Watershed Council, 2005). However, there were also some areas of concern. Water quality was shown to be affected by flow and the amount of precipitation, with wetter years having poorer water quality, which indicated that source loadings were an issue (Koning *et al*., 2006). While water upstream was found to be in the good to excellent range for water quality, it was found to deteriorate as it flowed downstream. The water quality in streams affected by agriculture and urban runoff were found to be in the poor to fair range (Oldman Watershed Council, 2005).

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Pesticides were detected in some water samples, but detections were as frequent or more frequent in urban stormwater outfalls as they were in agricultural irrigation return flows. Other forms of contamination were found in the river as well; it was determined that the contamination originated from a range of sources including wildlife, agricultural activity, and possibly human sewage contamination (Koning *et al.*, 2006).

Analysis of the scientific data collected and consultation with the key stakeholders in the basin led to the implementation of improved management programs throughout the basin, in both rural and urban communities. This included rural-based BMPs such as livestock exclusion fencing for the river, buffer strips, and livestock relocation, as well as education of residents about water management in urban areas (Koning *et al.*, 2006). Through collection of sufficient water quality data, collaboration, and a good understanding of the issues, changes were made that improved watershed health in the Oldman River Basin.

Accounting For and Addressing Governance Challenges

Sustainable management of water resources requires effective governance. A key finding from the Panel's review of the water and environmental governance literature is the fact that simplistic, "one-size-fits-all" solutions do not exist. Instead, the roles that key stakeholders can and should play in decision-making, the appropriate scales at which decision-making should occur, and the tools and approaches best suited to governance in particular areas are entirely context-dependent. Experiences from around the world broadly support engagement of non-government stakeholders in decision-making processes, and point to an increasing role for collaborative approaches that involve sharing of responsibilities and pooling of resources. However, Canadian and international experiences also draw attention to common governance challenges related to new ways of governing (Armitage *et al.*, 2012). For example, questions of legitimacy and accountability arise when locally-organized watershed partnerships and collaborative bodies become involved in decision-making. Similarly, efforts to integrate decision-making across a diverse range of contexts, such as land use planning, economic development, and water management raise questions about how much integration is possible, and how potentially conflicting policy goals should be balanced. Accounting for and addressing these kinds of governance challenges is essential to ensure the sustainable management of water resources for agriculture.

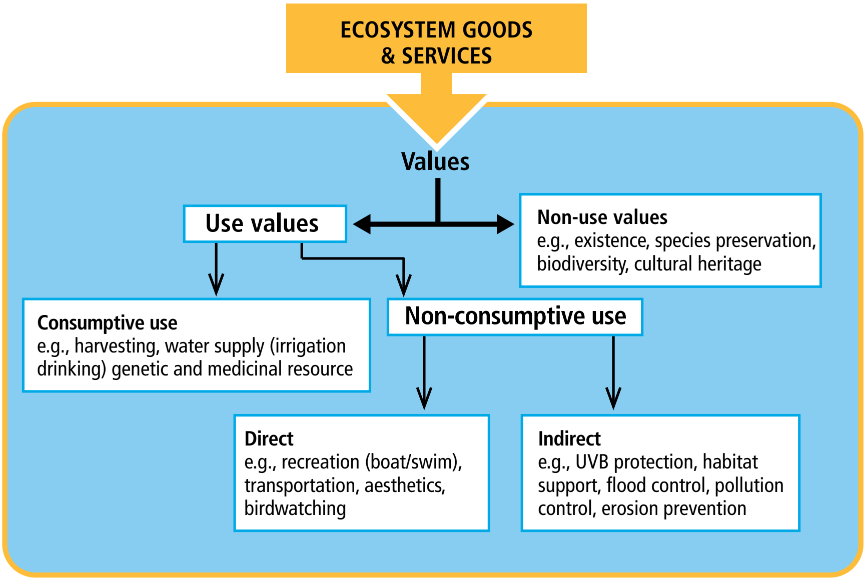
6.2 ECONOMIC INSTRUMENTS TO SUPPORT SUSTAINABLE WATER MANAGEMENT

This section explores economic instruments that can be used to support decision-making about water and to influence the behaviour of water users. Economic instruments are by no means the only tools that can be used to influence behaviour. However, experiences from across Canada and around the world demonstrate that economic instruments — when designed properly and implemented appropriately — can support the goal of sustainable water management. In particular, this section examines the role that can be played by economic valuation techniques, economic incentives, pricing, and water markets, relative to agriculture in Canada.

Economic Valuation Techniques

Many scholars, policy-makers, and water management professionals believe that capturing the full value of water (including the ecosystem goods and services it provides) is an important step towards overcoming the disincentives for conservation embedded in its "common pool" characteristics and promoting better stewardship of water resources (Millenium Ecosystem Assessment, 2005; NAS, 2004c). Economists have developed a number of valuation techniques that can assist in making decisions about alternative uses of water, as well as policy tools that can encourage efficient use of water and more sustainable behaviours. To be effective, these techniques and tools need to account for a broad range of potential values and the nature of the ecosystems within which the water resources are situated (Millenium Ecosystem Assessment, 2005; NAS, 2004c).

Establishing a total economic valuation (TEV) for ecosystem services is one technique that has emerged for assessing the value of the ecosystems supported by water resources (see Figure 6.2). One advantage of this approach is that it provides a way for assessing both the use (e.g., irrigation, drinking water) and non-use (e.g., biodiversity, cultural heritage) values of water. Use values can be further subdivided into consumptive and non-consumptive uses, with non-consumptive uses including both direct (e.g., recreation, transportation) and indirect (e.g., pollution control, habitat support) uses.



Adapted from NAS, 2004c

Figure 6.2

A Total Economic Valuation (TEV) Framework

This figure illustrates the total economic valuation approach to valuing ecosystem goods and services. Note that this approach seeks to incorporate both use (e.g., irrigation, recreation) and non-use (e.g., biodiversity, cultural heritage) values.

Various tools and approaches can be employed for establishing these values. Conventional economic valuation tools include those that attempt to reveal preferences through actual choices and behaviours (e.g., market price, travel cost, and hedonic tools); those that identify stated preferences based on responses to queries about perceived values (e.g., contingent valuation); and those that estimate values by estimating costs related to avoidance of losses (e.g., replacement cost and avoidance cost techniques) (Aylward *et al.*, 2010; Farber *et al.*, 2006; NAS, 2004c). A variety of non-monetary valuation methods also exist (e.g., asking people to rate preferences; seeking opinions from experts about choices that will lead to optimal outcomes; and focus groups of citizens) (Aylward *et al.*, 2010; NAS, 2004c; UNDESA, 2006).

The main challenges involved in the TEV approach are its inherent complexity and contestability. As discussed in a 2004 U.S. National Academies of Science report, assessing the value of ecosystem services can be particularly difficult given that “ecosystems are complex, dynamic, variable, interconnected, and non-linear, and because our understanding of the services they provide and how they are affected by human actions are imperfect and difficult to quantify” (NAS, 2004c).

Further, because of its importance to sustaining life and the many other non-monetary values attached to water (e.g., cultural value of water, aesthetic value of a landscape), some stakeholders reject efforts to establish economic valuations of water altogether (UNDESA, 2006). Even where non-monetary valuations are included in the "total valuation," there is often considerable scope for disagreement about the correct methods of valuation, the value to place on each valuation, and how to incorporate valuations into water policy and management decisions (Aylward *et al.*, 2010).

Despite these concerns, appreciation is growing for the usefulness of valuation approaches that combine conventional economic and non-monetary valuation techniques, so as to better reflect the "full value" of water resources (UNDESA, 2006). These methods can be combined with various decision support tools, such as scenario analysis or multiple criteria decision analysis, to arrive at a better understanding of the various costs and benefits of different courses of action. Decisions about how water resources will be used must flow from appropriate political and administrative authorities, taking into account the full range of stakeholder preferences, as well as other economic and institutional parameters. However, valuation methods are a powerful tool for informing decisions and building the consensus needed to support effective policy implementation (see Belton & Stewart, 2002; CCA, 2011; NAS, 2009).

Importantly, the implications for agriculture of a move to capturing the TEV of water remain unclear. For example, in most respects where water is used in agricultural production, it is non-substitutable. Plants require water for growth, and animals require water for drinking. Thus, while the Panel strongly supports the need for better information about the total value of water (economic, environmental, and social), it suggests that evaluation of the implications of a shift to TEV of water for agriculture should be a priority for research.

Economic Incentives

Economic incentives are another mechanism that can be used to help shape behaviour to preserve the quantity and quality of water resources. Examples include incentive payments for voluntary adoption of BMPs and payments for ecological services (PES). Each of these tools has certain advantages and drawbacks that should be taken into account when trying to achieve particular goals.

Incentives may take the form of payments for adopting particular BMPs, as in the case of the Canada-Saskatchewan Farm Stewardship Program (CSFSP) (AAFC and Saskatchewan Ministry of Agriculture, 2011). The CSFSP enables farmers to receive up to $50,000 towards the cost of implementing BMPs, such as adopting precision farming applications (e.g., variable rate controllers for fertilizer and manure application), planting vegetation to protect stream bank and shoreline areas, or constructing perimeter fencing to protect the environment from livestock. To be eligible for the program, farmers must complete an environmental farm plan to show how their actions will reduce the risks that their operations have on the environment. Farmers must also share in a percentage of the costs (the amount depending on the nature of the BMP). Similar programs have been put in place in other jurisdictions such as Ontario and Manitoba (AAFC, 2007b; Ontario Soil and Crop Improvement Association, 2010). An evaluation of a cost-shared program of this type in Ontario, the Rural Water Quality Program determined that financial incentives were a significant factor accounting for the voluntary adoption of BMPs by farmers (Dupont, 2010).

Incentive-based BMP programs can potentially limit the need for more intrusive regulations; however, the economic and environmental efficacy of such programs needs to be addressed on an ongoing basis. If not adequately targeted, some incentive programs may simply result in farmers receiving subsidies for investments in BMPs that they would have undertaken anyway (e.g., improvements in pesticide applicator technologies). In such cases, rather than providing a financial incentive, it may be better to promote these types of BMPs with communication and outreach programs that present farmers with the business case for voluntary adoption — thus lowering or eliminating the amount of subsidy that would need to be paid. In other cases, the environmental outcomes of the BMPs may be insufficient due to limited uptake under a voluntary scheme, particularly where the financial and human resource costs of adoption are higher (Young & Karkoski, 2000) and where farmers are unsure of their return on investment (Sparling & Brethour, 2007). As discussed in Chapter 4, the benefits of some BMPs are not well established, particularly within one given locale as opposed to another, raising questions about the economic efficiency of the incentives for adoption. The local physical and social environment needs to be considered when determining whether a BMP is suitable for a given area, and whether financial incentives are appropriate and needed.

Direct incentives can be created for the provision of ecological services. The PES approach seeks to establish market-like relationships rather than offering subsidies or cost-sharing arrangements. It also builds on contractual relationships between the providers of a specified ecological service, such as a farmer whose practices can promote water retention, and a buyer who represents public or private demand for such a service. In theory, these relationships would encourage the producer-seller to develop cost effective approaches to providing such services (Bohlen *et al.*, 2009; Shabman & Stephenson, 2007).

Bohlen *et al.* (2009), describe a pilot PES project in the U.S. Northern Everglades, in which ranchers were paid for improving water retention and reducing phosphorus runoff on their pastures to maintain water quality in a surrounding lake system. Demand for these services was created by several environmental regulations that aimed at restoring and protecting the natural Everglades ecosystems. State agencies acted as buyers and drew on a commitment of three million dollars in public funds and an equal contribution from a private foundation. While the project succeeded in improving water and ecosystem quality, it highlighted the following challenges that are commonly encountered with PES schemes:

- Identifying and documenting environmental services, which in many cases are not easy to quantify and verify, thereby indicating the need for a low-cost approach to monitoring and certifying the delivery of the services paid for.
- Developing contracts and payment schemes that ensure stable payment flows and offset financial risks for farmers, in particular in cases where the provision of the services requires up-front investments in water management infrastructure.
- Managing intersection and overlap with regulatory agencies and programs, such as agencies responsible for water management or environmental programs that regulate or control the activities the farmer needs to pursue to provide the service (Bohlen *et al.*, 2009).

In addition to these challenges, the Northern Everglades PES project highlighted the importance of involving relevant stakeholders and the beneficial impact of a “social entrepreneur,” in this case a conservation agency that is perceived as a neutral broker and can help to establish project objectives, establish contractual relationships, and offer advice in case of conflict (Bohlen *et al.*, 2009).

The Alternative Land Use Service (ALUS) program underway in Manitoba, Ontario, Alberta, Saskatchewan, and Prince Edward Island is one of the main examples of the use of PES. Like other programs of its kind, the ALUS program pays farmers for providing ecological services such as the preservation of wetlands (ALUS, 2011; Government of Manitoba, n.d.). Experiences from Europe, where the PES approach is used under the Common Agricultural Policy, provide some evidence that it does provide certain benefits (Power, 2010). For example, a survey of five European countries found agri-environment programs had marginal to moderate positive impacts on biodiversity (Kleijn *et al.*, 2006). In North America, the use of PES schemes is in its infancy. The concept may be useful in establishing alternative funding streams for water preservation on the agricultural landscape while exploiting market dynamics towards the development of cost effective approaches. However, research is needed to determine how PES might contribute to achieving sustainable water management in the context of Canadian agriculture.

Pricing

Pricing is a market mechanism that can promote sustainable behaviours by creating economic incentives for improved water management practices. In many jurisdictions, the prices charged for water only account for the costs of delivery rather than the "total value" of the resource, which includes opportunity costs, economic externalities, and social and environmental externalities. Raising the price of water to reflect its total value and the full cost of providing water services is one way of promoting more efficient use of water resources (UNDESA, 2006). With this approach, the price takes into account opportunity costs and any third party damages in addition to the costs associated with the operation, maintenance, and replacement of water infrastructure (UNDESA, 2006). However, common challenges associated with this approach include resistance to charging for an essential resource that has long been regarded as a "public good" with a tradition of being provided at low costs, and unease that higher costs will reduce access to water among lower income citizens (UNDESA, 2006).

These kinds of challenges are typical in the context of urban water supply. In the context of agriculture, a host of additional challenges are relevant. As discussed in Chapters 2 and 3, the volumes of water used by farmers can be very large. In many regions of Canada, farmers are self-supplied — for example, they take water from rivers, lakes, and groundwater aquifers using their own infrastructure. Thus, any price for water would in effect be a royalty collected by a provincial government rather than a fee to recover the cost of providing the service. Where farmers receive water from centralized systems, as is common in Alberta, Saskatchewan, and British Columbia, prices could be used in the same way they are in municipal settings. However, significant questions about the ability of farmers to pay a higher price for water exist. More fundamentally, in some areas of agricultural production there are significant limitations on the ability to conserve water. For example, 80 per cent of water demand on a typical livestock farm is for drinking by animals (Agriculture Canada & Ontario Ministry of Agriculture and Food, 1994); thus, the ability of livestock producers to reduce water use through increased efficiency is limited relative to other sectors.

The Panel concluded that these kinds of challenges can be overcome in some sectors, but this will require working with stakeholders to establish different prices for differing uses (e.g., drinking water, irrigation, industry use). Appropriate attention will have to be paid to the principles of equity, fairness, and the social and private benefits derived from particular water uses (Horbulyk, 1995; UNDESA, 2006). The characteristics of simplicity, transparency and predictability are also essential for success, to ensure pricing schemes are fully understood by all stakeholders (UNDESA, 2006). Incentives to improve efficiency (thereby helping users to reduce their own costs as prices are raised) may also be introduced at the same time to help offset some of the increased costs for those willing to invest in efficiency gains (in effect creating a "double incentive"). Establishing the right mix of pricing policies requires ongoing negotiations, monitoring, assessment, and adjustment. However, whether or not improvements in water use efficiency in agriculture can be achieved more effectively through pricing mechanisms as opposed to other tools (e.g., regulations, incentives for upgrading infrastructure) should be a subject for future research.

Water Markets

Tradable water rights are another market mechanism that can be used to promote efficient use of water resources because they permit shifting water from low value to high value sectors — sometimes within the agricultural sector, but often from agricultural to non-agricultural uses. Water markets typically involve transferring the right to use water based on "the type of use, place of use, point of diversion, or time of use" (Australian Government, 2011b; Libecap, 2010; Veeman *et al.*, 1997).

Various mechanisms have been developed for both the temporary and permanent transfer of water using economic tools. These include water banks, in which there is a central institution for buyers and sellers with set prices; bulletin board markets that operate like water banks but have no central institution that sets prices; double-auction markets, where buyers and sellers submit sealed bids for water; derivative markets, where options and forward contracts are used to trade water temporarily; and environmental leasing and purchasing programs, where irrigation water is purchased to increase in-stream flows (Hadjigeorgalis, 2009). By establishing a form of "property rights" for a particular allocation of water, the purpose of tradable rights markets is to create an incentive for users to engage in conservation by enabling them to trade unused surplus amounts to other users. The result may be investments in more efficient technologies, better management practices, or a shift from less productive to more productive uses (e.g., switching to crop types that use less water). Market trading in this way can also help move water from areas of surplus to areas of scarcity (whether the imbalances are caused by normal flow rates or climate variability), thereby assisting in balancing out user needs across a region. In turn, many analysts suggest that this can also promote investment in infrastructure and methods to enhance water conservation, and an increase in the water productivity of a given area (see Anonymous, 2009; Grafton *et al.*, 2009; Rosegrant & Gazmuri, 1995; Thobani, 1995). Market trading also is being used in Australia in an attempt to improve environmental conditions.

Although only a small proportion of the world's water resources are managed by markets, tradable water rights markets have been implemented in a number of jurisdictions. Market mechanisms are primarily concentrated in Chile, Australia, and the western U.S. (Bjornlund & McKay, 2002; Hadjigeorgalis, 2009). As a federation and a Commonwealth country, Australia is a particularly relevant international example for Canada. Following a series of reforms in the 1990s and 2000s, water markets have become a key element of the water allocation systems of Australia's states and territories. The market for trading water has now become relatively sophisticated, with irrigation infrastructure operators managing many of the functions of the water trade (including approvals) and designated facilitators, who connect buyers with sellers (Anonymous, 2009; Australian Government, 2011b; Grafton *et al.*, 2009; Young, 2008a). Market trading is also being used to transfer water from human purposes to meet environmental needs. For example, in Australia's Murray-Darling Basin, the Commonwealth Environmental Water Holder acquires water entitlements through direct buybacks of water entitlements from irrigators and through savings from infrastructure upgrades; these entitlements are managed to increase flows for rivers and wetlands (Australian Government, 2010, 2012).

Water markets also exist in Canada. In Alberta, users have access to water through licences obtained under the prior allocation system established through the *Water Act* (Alberta Environment, 2003). In this system, senior licence holders (with seniority determined by the date of the licence) have the right to their established allocation before junior licence holders. In 1999, a system to facilitate temporary assignments and permanent transfers of water was established. Holders of licences may transfer all or part of their allocation to another person or corporation. However, transfers are closely regulated. They are only permitted where an approved water management plan is in place that allows transfers, or through an order from the Lieutenant Governor in Council. The price charged for the water transferred is established by the buyer and the seller. In the case of permanent transfers, the government is also able to withhold 10 per cent of the water right for environmental purposes (Alberta Environment, 2003).

As with other policy tools, there are concerns and obstacles associated with market mechanisms. One barrier is public unease over the commodification of a resource that traditionally has been perceived to be a common good or human right (UNDESA, 2006). Others question the market's ability to provide for non-market environmental needs (Bakker, 2007a). Experiences in jurisdictions such as Chile, during the first phase of water market activity, raised legitimate concerns (Bjornlund & McKay, 2002). Another challenge relates to the tendency towards concentration of water rights ownership, particularly where prices rise under conditions of scarcity: if wealthier farmers are able to purchase the bulk of the rights, smaller farmers may be pushed out of the business. However, it is important to remember that regulations and public involvement processes can be used to ensure that public values, including environmental needs, are protected and that rules are followed (Anonymous, 2009; Horbulyk, 2007).

Overall, water trading efficiency in a given market will depend on many factors that are specific to a given location, such as the physical infrastructure, legal regime, supply and demand of water, and the quantity of buyers and sellers (Rosegrant *et al.*, 2009). For example, in the case of Alberta, the creation of water markets was facilitated by the existence of three important preconditions: a prior allocation system that established a hierarchy of rights holders; the physical infrastructure needed to move water from sellers to buyers; and an irrigation economy that demanded large volumes of water. The Panel notes that these pre-conditions do not exist in all other parts of Canada, meaning that the relative significance of water markets as a tool for dealing with water scarcity that affects agriculture is highly variable.

6.3 KNOWLEDGE TRANSFER AND STAKEHOLDER ENGAGEMENT STRATEGIES

Section 6.2 examined a range of economic instruments that can be used to change behaviour. However, the reasons for individual behaviour regarding water are complex, and linked to the many values that water has in society; these values are both economic and non-economic in nature. Thus, achieving the changes in behaviour that will contribute to sustainable water management in agriculture requires engaging different drivers that motivate behaviour (Lamba *et al.*, 2009). For example, Atari *et al.* (2009) found that farmers who participated in Nova Scotia's environmental farm plan program — a key stewardship initiative that exists in provinces across the country — were motivated to participate much more strongly by non-financial considerations than by monetary considerations. The three most important drivers revealed through this study included helping to publicize positive farm stewardship practices; improving relationships with non-farming neighbours; and complying with government environmental regulations (Atari *et al.*, 2009).

Studies such as this point to the key role played by effective communication and knowledge transfer. The success of actions aimed at promoting water sustainability relies on stakeholder participation in a given solution, and their sense of responsibility in a given environment (e.g., local, regional, or within a basin). The individual views and interests of each stakeholder should be identified before solving issues, so that these interests can be appropriately considered. This can be achieved through numerous mechanisms. In this section, the focus is on social learning: the development of knowledge, skills, and attitudes, by connecting to others (colleagues, mentors or experts) via our social networks of belonging (real or virtual) (Cerf *et al.*, 2000; Reed *et al.*, 2010).

Worldwide concern about conserving the environment has increased in the last few decades (Fowler, 2002; Goss & Barry, 1995; Salazar-Ordonez & Sayadi, 2008). These concerns have translated into policies that impact agriculture production (Fowler, 2002; Salazar-Ordonez & Sayadi, 2008). A key issue for scholars and practitioners is finding ways to make public participation effective (O'Faircheallaigh, 2010). Public or stakeholder engagement can have a number of objectives that include increasing the transparency of political decisions; increasing social acceptability of policies; involving users in the adoption of planned measures; and adapting policies to specific local, natural, and social circumstances (Steyaert & Jiggins, 2007). In addition to these objectives, Stewart & Sinclair (2007) identified a list of public participation benefits: "access to local knowledge, broadening the range of solutions considered; avoiding costly litigation; strengthening the democratic fabric of society; acting as a vehicle for individual and community empowerment; and promoting broadly-based individual and social learning" (O'Faircheallaigh, 2010; Stewart & Sinclair, 2007).

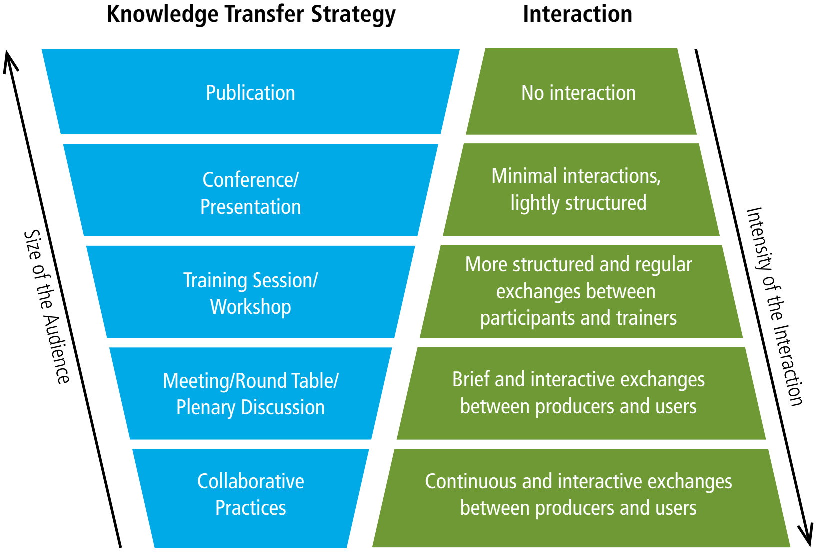
The Panel believes that public engagement does not just mean diffusing information in a one-way communication process. Effective public engagement in water governance and management involves dynamic, participative communication among members of the public, water managers, and policy-makers. Many of the collaborative processes discussed previously are grounded in this assumption. At the same time, public opinion limits the actions that can be taken by governments (and policy-makers) (Owen *et al.*, 2000; Pietsch & McAllister, 2010). If the public agrees with the experts, the policy put forward is likely to have important and extensive effects in a short time; however, if members of the public are skeptical, or hesitate because the required changes have a significant impact on their everyday lives, the policy might not be accepted (Pietsch & McAllister, 2010). This is why transparency and effective knowledge transfer (communication) are key factors in promoting sustainable water use in agriculture and informing the public debate and policy-makers about the sustainability of agriculture.

Sustainable water management in agriculture cannot be achieved without transferring information about good agricultural practices and strategies in a manner that ensures a high level of compliance from farmers and surrounding communities. Consequently, communication, diffusion, and adoption of new management practices are essential subjects of study (Compagnone *et al.*, 2009; Röling & Wagemakers, 2000). Problems and challenges related to the diffusion and adoption of innovative practices and strategies are not yet well understood in Canada. Similarly, communication has, for the most part, been analyzed only with a “science extension, top-down” perspective. This current top-down approach for technological transfer is based on the notion that only a few handpicked, informed/convinced potential users are needed to reach a wide spectrum of their peers. In many cases, this approach has been shown to be ineffective.

In agriculture, there is a significant gap between available knowledge and the use of that knowledge (Röling, 2009). Adopting sustainable water management practices, strategies and technologies involves complex processes that are influenced by a multitude of socio-economic, political, and technical conditions. As a result, a better understanding of these conditions is required (Leeuwis & van den Ban, 2003). Tools, strategies, and mechanisms that can help the diffusion and acquisition of new knowledge, practices, and technologies are therefore essential (Bessette, 2004; TRAME, 2007). This is true at the farm scale, where technologies and practices such as those discussed in Chapter 5 can play an important role in shifting to more sustainable water management if they are used, as well as in the context of more effective governance (Section 6.1). For example, strategies for adapting the agricultural sector to current and anticipated climatic variability are well understood in the literature (Wall & Smit, 2007; de Löe *et al.*, 2001). However, implementation of these strategies across Canada is highly variable (Dryden-Cripton *et al.*, 2009; Wall & Smit, 2007).

Adapting communication techniques to achieve different objectives and to reach diverse stakeholder groups can be problematic. Communication strategies should target both the primary audiences (e.g., farmers and their families) and the intermediate influential audiences (such as opinion leaders) (Blackburn, 1994; Swanson *et al.*, 1997; TRAME, 2007). Communication tools should be consistent with the desired objectives; the tactics used (e.g., popular articles, symposium participation, educational tools, communities of practice, use of agricultural spokespersons) should vary depending on the target audience (e.g., farmers, municipal representatives, general public) to maximize the potential that the ultimate goal is achieved: raising awareness or prompting change in farm practices (Bessette, 2004; Brisson *et al.*, 2010).

Numerous knowledge transfer strategies exist, each having a different intensity of interaction with the target audience (see Figure 6.3). Knowledge transfer (communication) strategies must be tailored to both the type of information that needs to be communicated and the objectives to be achieved. Barriers and benefits have an impact on how intended audiences will use the knowledge that is conveyed



Adapted and translated from Lemire *et al.*, 2009

Figure 6.3

Interactions Required by Different Knowledge Transfer Strategies

This figure illustrates the different knowledge transfer strategies in relation to the size of the audience they reach and the intensity of the interaction each strategy requires.

to them (Lemire *et al.*, 2009). Therefore, no single knowledge transfer strategy can be used effectively in all situations (Lemire *et al.*, 2009). In the remainder of this section, three knowledge transfer approaches that are particularly relevant to agriculture are discussed: *diffusion strategies*, *appropriation strategies*, and *extension work*. They differ primarily by their objectives and the size and type of the intended audience.

Diffusion Strategies

The purpose of diffusion as a knowledge transfer strategy is to ensure that a variety of stakeholders are able to access and understand new information (Lemire *et al.*, 2009). Effective diffusion requires specialists who can provide information to a large audience whose members are often knowledgeable on the subject matter at hand (Lemire *et al.*, 2009). Since this strategy brings information to a wide audience, it is not an efficient tool for conveying how to use that knowledge in concrete and detailed terms (Lemire *et al.*, 2009). Social media are a good example of this type of knowledge transfer (Box 6.3).

Box 6.3
Social Media as an Example of a Diffusion Strategy

To maximize the potential for success, communication about sustainable water management practices and strategies must take advantage of new information and communication technologies. The internet has facilitated the gathering and sharing of information among farmers, and between farmers and the public, and has aided in the formation of agricultural networks (Godfrey & Wood, 2003). Websites such as FarmIssues.com offer information for the public about farm concerns and provide links to relevant agricultural organizations. Educating the public is an important factor in public perception and ultimately, in policy-making. Organizations whose main mandate is to inform farmers and allow them to share their experiences and knowledge (e.g., Farm and Food Care Ontario) have effective websites that are used to disseminate information. Facebook pages, twitter feeds, blogs, and online research abstracts are some of the digital media options that can be used for knowledge transfer activities (Elissade *et al.*, 2010). The amount of interaction that occurs using social media is highly variable. Blogs tend to be "one way", although most permit comments. In contrast, Facebook pages can be highly social and lead to the formation of interactive communities.

Appropriation Strategies

Appropriation strategies for knowledge transfer allow the integration and application of knowledge (Lemire *et al.*, 2009). These strategies require training services and subject specialists, and involve multidirectional exchange of information (Lemire *et al.*, 2009). The intended audiences for knowledge transfer activities based on appropriation strategies are much smaller than those targeted through diffusion strategies; additionally, these strategies include a more diverse range of stakeholder groups. An example of an appropriation strategy includes the development of a community of practice (see Box 6.4). A main goal of appropriation strategies typically is to learn (or solve a problem) using the knowledge and experience of each participant in a well-structured or organized manner. Appropriation strategies usually permit more effective engagement of participants than diffusion strategies because of the increased amount of interaction that occurs (Lemire *et al.*, 2009).

When online tools are used to form communities of practice, it is essential that the desired audience has access to the necessary tools (computers, internet connections, etc.) and knows how to use information technology. In the agricultural sector, adoption of internet-based tools for knowledge translation is highly variable, with some farmers being extremely sophisticated users, and others slower to adopt these tools. Thus, in the context of agriculture, Yiridoe *et al.* (2010) found that while online knowledge strategies are growing in popularity, they have not replaced communication tools that have long served rural areas, including peer communication, farm newsletters, agricultural magazines, and demonstrations and field tours.

Box 6.4

Communities of Practice as an Example of an Appropriation Strategy

Communities of practice, particularly those known as virtual communities of practice (VCPs) are new forms of knowledge transfer initiatives that are used with increasing regularity. For this discussion, a community of practice can be defined as "a group of people bound together by shared expertise and passion for a joint enterprise who develop a shared repertoire of resources (tools) enabling the pursuit of their endeavours" (from O'Kane *et al.*, 2008; Wenger *et al.*, 2002).

Communities of practice offer not only an information and discussion space, but also an interactive platform for learning, problem solving, sharing experiences, and exchanging knowledge between people with a common interest (Lave & Wenger, 1991; O'Kane *et al.*, 2008). The community of practice model can be real or virtual, with the latter requiring support by information and communications technologies. For example, within a rural water management framework, a VCP could allow for an exchange of experiences between farmers and/or rural communities, energizing the sharing of information through success stories, and lessons learned. This type of knowledge transfer activity is typically done through emails, videoconferences, forum discussions, etc., all of which can be documented and archived for future reference. VCPs are particularly well-suited for rural and agricultural environments as they overcome the inherent problem of distance between stakeholders (e.g., see Karetsos *et al.*, 2008).

Extension Work

Extension work is a tool that can be used in a variety of knowledge transfer strategies. In terms of agriculture, extension involves a variety of public and private efforts to transfer knowledge, educate producers, and mobilize them to take action (Feder *et al.*, 2001). Extension can involve transferring technologies, transferring management practices to mobilize and organize farmers and rural communities, and building the capacity of farmers and rural communities (e.g., by building human resources, increasing the capacity to gather and use market intelligence, and improving farm management skills) (Feder *et al.*, 2001).

The roles of extension workers are changing from “traditional technology dissemination” to “organizing rural producers, forging links with markets, and playing a brokering role with other actors in the agricultural innovation system” (Rivera & Sulaiman, 2009). Acceptance of new technologies by farmers depends on the economic incentives presented to them (Tollefson & Wahab, 1996). Transfer of technology and extension are critical to this acceptance. Motivated, well-trained extension workers are crucial for effective information transfer (Tollefson & Wahab, 1996). The challenges faced by extension workers include delivering information effectively and ensuring that farm clients utilize new technology properly (Tollefson & Wahab, 1996). Box 6.5 provides an example of a successful extension-based initiative developed originally in southern Ontario. Evaluations of this program highlighted the critical role played by on-the-ground extension workers who worked directly with farmers on their farms. Importantly, the example of the Rural Water Quality Program in Ontario also highlights the role that capacity building can play in helping farmers become a kind of extension worker within their own communities.

Box 6.5
The Rural Water Quality Program

In many watersheds, agricultural activities are an important contributor of nutrients, pathogens, and other threats to water quality. As demonstrated by experiences in PEI, the success of regulatory approaches to dealing with these threats has been highly variable (see Box 4.1). As a result, many jurisdictions are using stewardship-based approaches to support the implementation of BMPs on farms. The Rural Water Quality Program created by the Regional Municipality of Waterloo (RMOW) in 1998 is a long-standing, successful example that was eventually expanded throughout the Grand River watershed, and beyond (Simpson *et al.*, 2009). The objective in this program is to protect groundwater and surface water quality by working closely with farmers to identify appropriate BMPs, and then implementing these measures on a cost-share basis. The availability of funds for sharing the costs associated with BMP implementation was a key driver of success (Dupont, 2010). However, other acknowledged drivers for success of the program included the partnership approach (among the RMOW, local and provincial farm organizations, the Grand River Conservation Authority, and provincial government agencies) (Lamba *et al.*, 2009). Building the capacity of farmers was an explicit outcome of the program. Ultimately, engaging farmers as leaders and drivers proved to be essential (Simpson *et al.*, 2009).

6.4 EMPLOYING EFFECTIVE GOVERNANCE AND POLICY TOOLS TO SUPPORT SUSTAINABLE MANAGEMENT OF WATER FOR AGRICULTURE

Combining the right mix of governance strategies, economic instruments, technological advancements, and knowledge transfer strategies can assist in promoting sustainable management of water for agriculture. The key factor for success is getting the right mix of policy tools for the right context and communicating the purpose of those tools effectively to ensure adoption of desired behaviours. As discussed previously, no single strategy can be used in all situations as objectives and audiences can vary. The best knowledge transfer approach uses a combination of strategies to reach each targeted audience in an efficient and accessible manner (Fondation de la faune du Québec & Union des producteurs agricoles, 2011; Lemire *et al.*, 2009).

Based on its research and deliberation, the Panel concludes that sound governance, effective use of appropriate economic instruments, and effective knowledge transfer strategies are essential prerequisites to sustainable water management in agriculture. For example, experiences from across Canada and around the world demonstrate conclusively that while BMPs are known, and effective technologies are available, the extent to which these are adopted depends on a host of considerations, including the regulatory environment, the existence of appropriate incentives, the availability of knowledge, and the capacity to implement practices and technologies. Similarly, while knowledge of the adaptation strategies needed to respond effectively to climate change in the agricultural sector is relatively good and increasing in the literature, the primary constraints to their adoption relate to the kinds of considerations addressed in this chapter.

Review of Key Findings

- Governance for water in Canada is considerably more complex today than it was in previous generations. Consequently, a host of new challenges exist relating to effectiveness, capacity, legitimacy, and accountability. As understanding of how best to address these is uneven, this represents an important area for future research.

continued on next page

- Though no single "one-size-fits-all" framework can be right for all jurisdictions (given differences in legal regimes, institutional settings, and socio-economic contexts) the Panel believes there are several principles that have been shown to be effective in supporting sustainable management of water resources for agriculture and other human and environmental purposes. These principles include:
    - Ensuring governance operates at the appropriate scale;
    - Integrating land-use planning with water management decisions;
    - Involving affected stakeholders in the decision-making process; and
    - Incorporating knowledge into the decision-making process.
- Appropriately designed and implemented economic instruments also can support the goal of sustainable water management. Examples include economic valuation techniques, economic incentives, pricing, and water markets.
- Knowledge transfer strategies are another important channel for influencing behaviours. No single strategy can be used in all situations, since objectives and audiences vary. A better understanding of which methods are most effective at communicating information about sustainable use of water is needed to ensure that relevant material reaches targeted audiences in an efficient and accessible manner.

7

Conclusion

- Main Question
- Sub-Questions
- Final Thoughts

7 Conclusion

Water is essential to human activities and natural ecosystems. It is also an increasingly scarce resource. Population growth and rising incomes are heightening the competition for water and other resources, just as uncertainties connected with climate change are increasing the complexities of ensuring that resources are used efficiently and that risks to infrastructure and output are managed effectively. Improving — or even sustaining — living standards, quality of life, and global health in the coming decades will depend on our ability to enhance water use efficiency and maintain water quality. Moreover, it is clear that a "business as usual" approach will not be sufficient to do so. There is a need for a concerted, integrated approach that reduces impacts on water quality in all areas, while optimizing the use of land, water, and other resources across economic sectors, political boundaries, and regional ecosystems.[38]

Agriculture has an important role to play in meeting these global challenges, as agricultural production can have major impacts on the availability and quality of water resources. Two distinct aspects of agricultural water use should be noted. About 70 to 80 per cent of global harvested area (de Fraiture & Wichelns, 2010; Molden *et al.*, 2007b) and more than 97 per cent of Canadian harvested area (AAFC, 2011c) is fed by precipitation in the form of rain and snow. In precipitation-fed agriculture, improving water use efficiency and crop yields can increase productivity per acre, thereby increasing total production without necessitating an expansion of the cultivated area. In a world with increasing competition for land, water, and other resources, this can be an important contribution to sustainability. Other agricultural activities, such as irrigation and intensive livestock watering, withdraw water from rivers, lakes, reservoirs, and groundwater. In these uses, and in particular irrigated agriculture — which represents the bulk of water consumption in agriculture — improvements in water use efficiency can also make an important contribution to agricultural productivity and the availability of water resources, particularly in water-stressed areas where the extraction of water for irrigation competes with other uses.[39]

In all agriculture, including precipitation-fed, irrigation, intensive livestock, and other activities, progress also can be made in mitigating impacts on water quality from nutrients, pesticides, and other environmental risks connected with

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[38] There are many reports and articles that outline the nature of this global context. This paragraph draws upon Godfray *et al.*, 2010; The World Bank, 2010; UNESCO, 2012.

[39] For a fuller discussion as to the relative contributions to precipitation-fed and irrigated agriculture, see Box 2.1 in Chapter 2 of this report.

agricultural production, the costs of which can be significant. For example, a 2011 European Nitrogen Assessment (Sutton *et al.*, 2011) estimated that the environmental damage related to reactive nitrogen effects from agriculture in the European Union at between €20 and €150 billion per year. This compared to a benefit of nitrogen fertilizer to farmers, which was valued at between €10 and €100 billion per year. While Canadian use of manures and fertilizers is less intense than the EU, significant local and regional issues arise. Agricultural impacts on water quality are thus complex issues requiring careful scientific assessment to determine the effects, the costs and benefits of various mitigation strategies, as well as the trade-offs involved.

There are tremendous economic opportunities for the Canadian agriculture sector as a result of the future increases in global demand for food and other agricultural products. The Panel observes that Canada has the land mass, financial capital, technology, and expertise to make significant contributions to meeting these demands. There are, however, a range of issues in land and water management, public policy and regulation, social perceptions, and other areas that will need to be effectively managed to maximize these opportunities and ensure the sustainability — and indeed, the viability — of the sector. This report identifies several management strategies and research investments that can assist in achieving these goals.

Table 7.1 provides an overview of the major issues that may affect sustainable management of water for agriculture and their associated risks/uncertainties, together with potential management strategies and the science and knowledge investments that can be made to advance each strategy. The remainder of this chapter provides the Panel's direct responses to the main question and sub-questions posed by the sponsor, all of which contribute to further elaboration on the essential science and knowledge requirements to guide sustainable management of water for agriculture. As noted throughout this report, the precise mix of issues, risks, uncertainties, strategies, and research needs will be somewhat different for each agricultural sub-sector and locale. As a result, it is not possible to provide a comprehensive review by sector and location within the scope of this report; however, the following table provides an overview of some key cross-cutting issues based on current information. Conducting further, in-depth research on how to best respond to these overall issues within specific sub-sectors and locale should be high on the list of research priorities.

Table 7.1

Management Strategies and Research Investments for Promoting Sustainable Management of Water for Agriculture in Canada

Issues	Risks/ Uncertainties	Management Strategies	Research Investments
Market Conditions	Missed opportunities due to lack of resources, public perception, skills shortages, knowledge gaps about market changes, or other factors.	Invest in research to better understand and mitigate environmental, social, economic, and informational risks to market development.	Economic and policy research on market trends in agriculture. Identification and development of human resources skills and needs.
Water/Land Resource Management	Missed opportunities to capitalize on rising global demand for food and other agricultural products (e.g., biofuels, bio-industrial products) due to ineffective management of finite water and land resources. Potential for negative agricultural impact on the water environment.	Improve sustainable management of land, water and other resources. Adopt adaptive management to provide robust strategies to accommodate uncertainty in water futures.	Effective monitoring and modelling to improve operational management, and develop better understanding of the resource base, potential changes over time, and evaluation of investments in BMPs, governance, and technology. Research to develop better understanding of complex interconnections among land use, water management, environmental flows, and ecosystem health.
Policy and Regulatory Risks to Water Access for Agricultural Production	Access to technology and investments in management practices affected by uncertainties and/or unanticipated changes in regulatory environment.	Work towards improving clarity and stability of the regulatory environment. Improve sustainability of agricultural production to reduce potential for sudden changes in regulation.	Research on best practices in governance to incorporate concerns of stakeholders and enhance public support. Research on BMPs, policy tools, and technological options to improve sustainability.

continued on next page

Issues	Risks/ Uncertainties	Management Strategies	Research Investments
Social Perceptions about Water Use in Agriculture	Possibility that negative perceptions about water use efficiency in agriculture may contribute to limiting the social licence for expansion of production, thereby limiting the ability to take advantage of expanding opportunities. Perceived risks associated with agriculture's impact on the water environment.	Improve communication regarding increases in water use efficiency and reductions in the environmental impacts of agricultural production. Engage stakeholders and contribute to informed debate on water management decisions.	Effective monitoring to develop better understanding of the resource base, potential changes over time, and evaluation of investments in BMPs, governance, and technology. Research on improving knowledge transfer and exchange among stakeholders.
Governance and Water Management Decision-making	Increased complexity of governance for water. Emergence of new ways of governing that may bring new challenges. Lack of coordination and integration can undermine governance effectiveness.	Incorporate principles of effective governance and suitable policy tools to support informed water management decisions. Identify opportunities to coordinate among jurisdictions at the regional and national levels for mutual benefit.	Research on best practices to address current and emerging governance challenges, and to facilitate coordination and integration of water management decision-making.
Climate Change (Canada)	Heightened uncertainties owing to changes in temperature and CO_2, increased instances of extreme weather events, changes in timing and extent of precipitation, and changes in environmental flows of water.	Explore potential for expansion of growing season, increased areas of production, and changes to the viability of particular types of crops in a given location (e.g., due to changes in precipitation, temperature variations). Build resiliency and adaptability through a combination of technologies and management practices, leading to a more robust agricultural system.	Research on climate change impacts and adaptation on regional scales to better inform investment decisions by agricultural producers, governments, industry, and other stakeholders.

7.1 MAIN QUESTION

What additional science is needed to better guide sustainable management of water to meet the needs of agriculture?

The Panel has identified several areas where additional science — defined broadly to include the natural, social, and health sciences as well as engineering and the humanities — can contribute to guiding sustainable management of water to meet the needs of agriculture.

Priority areas include:

- Achieve a better understanding of risks and uncertainties in areas such as market conditions, competition for land water resources, and climate change to inform management decisions, leading to more effective management practices and outcomes (discussed in Chapter 2).
- Improve monitoring information targeted to specific areas of concern on a risk-based basis, as well as enhanced scientific capacity for the interpretation of these data, to foster better understanding of Canada's water resource base and ongoing changes in hydrology, water quality, ecology, and climate, and to facilitate adaptive management (discussed in Chapter 3).
- Achieve a better understanding of the complex interactions between land management and water resources, including assessment of the economic and environmental efficacy of BMPs and the potential for conservation agriculture and ecosystems services approaches to management of natural resources (including land and water) (discussed in Chapter 4).
- Improve knowledge of promising farm-scale technologies and research priorities, contributing to better water use efficiency, reduced environmental impacts, and sound investment decisions by governments, industry, and agricultural producers (discussed in Chapter 5).
- Build a foundation for sustainability by adopting appropriate governance structures, valuation techniques, economic incentives, and knowledge transfer strategies to facilitate better management decisions, improve uptake of sustainable practices, and enable the agricultural community to build strong working relationships with other sectors and stakeholders to resolve cross-sectoral issues (discussed in Chapter 6).

In each of the above areas, there is no "one-size-fits-all" solution that can be applied in all jurisdictions, since the economic, environmental, political, regulatory, and social conditions vary considerably from one locale to another. Therefore, throughout this report, the Panel has sought to offer a range of options from which different stakeholders can select moving forward, given their respective responsibilities and needs. Reponses to the following sub-questions discuss these options in more detail.

7.2 SUB-QUESTIONS

Sub-Question 1

What is the state of water resources in Canada for agricultural use in Canada and how is this affected by major competing rural demands, such as consumption by local industry and recreational use?

Current State of Water Resources

Water use for agriculture has two distinct aspects. The dominant agricultural land use (> 97 per cent) is for precipitation-fed arable agriculture (AAFC, 2011c), which in Canada means agriculture fed by rain and snow. While agriculture has changed, and continues to change, for the rural environment, with associated effects on water quantity and quality, this use of natural precipitation is generally not in competition with other uses. However, other agricultural water uses, for example irrigation and livestock watering, are withdrawn from rivers, lakes, reservoirs, or groundwater, and may compete with other water uses, including municipal supply, industry, power generation (both for hydropower and the cooling of thermal power stations), and the environmental flows needed to sustain wetlands and riparian and aquatic habitats.

Despite its high per capita availability of fresh water, Canada is not "water rich." The majority of Canada's rivers flow north, away from the major concentrations of people and agriculture (Corkal & Adkins, 2008; Statistics Canada, 2010a). There are many regions across the country where pressures on water are already a serious concern. Vast areas of the Prairies, interior valleys of British Columbia and parts of southwestern Ontario are semi-arid to sub-humid and have insufficient precipitation for crop production on a regular basis (see Chapter 3). These are areas where irrigation is beneficial, but pressures on water resources are increasing, and in some areas of intensive irrigation development (e.g., Southern Alberta), water resources are already fully allocated. In addition to the quantity of water, there are also many jurisdictions where water quality is a concern as a result of contamination linked to human activities, including agriculture (see Chapters 3 and 4). While pollution is often the result of multiple sources, factors of concern for agriculture include nutrients from fertilizers and manures, pathogens from livestock wastes, veterinary medicines, and pesticides. For example, as documented in Chapter 3, the risks of nutrient contamination of surface water and groundwater are of particular concern, and have been increasing in agricultural watersheds across Canada over the past several decades. In addition, although concentrations generally fall below Canadian limit values where they exist, pesticide residues have been detected in the surface waters of all provinces and in 2 to 40 per cent of the wells surveyed in British Columbia, Alberta, Saskatchewan, Ontario, Nova Scotia, and Prince Edward Island (Cessna *et al.*, 2010). Since agriculture requires access to fresh water in sufficient quantities and quality, both water availability and contamination are concerns. Pressures on water quantity and quality can be caused by a range of factors that vary with location and over time; as these pressures increase, agriculture must work towards more sustainable management of water use and consumption.

Overall, Canada does not have the information needed to gain a complete picture of the state of water resources, as there are insufficient data on both water quantity and quality in many regions. Collection of data across the country is essential for many reasons. A complete national picture of the state of water resource quantity and quality is needed, since large climatic, ecological, industry, and population variations make the situation in each region unique. Time-series data are required to determine how water quantity and quality are changing with time and to monitor the effectiveness of new policy initiatives. While much national monitoring is of major rivers, information is needed for the small agricultural catchments relevant to monitoring the effects of agriculture on the environment, including the role of BMPs; in association with this, detailed research level data are required for selected locations to develop the science and management tools needed to guide policy. Finally, there is a need for a wide range of data for operational management of water resource systems, and for forecasting river flows and agricultural water needs. The need for additional water monitoring is discussed further in the Panel's responses to Sub-Questions 2 and 4, and the associated need for modelling and forecasting tools.

Competition Among Water Users and the Environment

Agricultural activity accounts for only eight per cent of water withdrawals in Canada, ranking behind thermal power generation, manufacturing, and municipal use. Most water withdrawals for non-agricultural sectors are non-consumptive, with the majority of the water used being returned to the source. Overall, agricultural activity consumes far more water than any other user (66 per cent) with the vast majority going towards irrigation (see Chapter 2). Currently, there are approximately half a million hectares of irrigated cropland in Canada, with the large majority located in Alberta and British Columbia (Statistics Canada, 2011b). Since irrigation provides drought resistance, it may become more important in the future as climate variability increases; however, in many regions that currently have significant areas of irrigated cropland, there is growing competition with other uses. In some cases, irrigation can be sacrificed when essential uses are at risk. In 2009, for example, the water available for agriculture was limited along the Nicola River in British Columbia to ensure that salmon had enough water to spawn (British Columbia Ministry of Environment, 2009).

All users of water, including agriculture, are competing with the environment for water resources (see Chapter 2 and 3). The health of water flows, defined as the "quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to people" (Hirji & Davis, 2009) must be maintained. Water flows provide beneficial ecosystem services such as water for humans and animals, support for aquatic and terrestrial ecosystems, flood protection, navigation routes, amenity and recreational opportunities, and waste dilution and removal (Hirji & Davis, 2009). Water stress results when the demand for water exceeds the limits needed to maintain a healthy environment; currently, some areas of the country (e.g., the Prairies and parts of British Columbia) are already experiencing severe water stress (NRTEE, 2010a). A 2009 World Wildlife Fund report described the Saskatchewan River, home to much of Canada's agricultural production, as the most threatened in Canada with respect to environmental flows.

Future State of Water Resources

Developing a better picture of the future situation of water, on a variety of temporal and spatial scales, is crucial for understanding and managing future risks and capitalizing on emerging opportunities for the agricultural sector. However, there are large uncertainties associated with the future availability of water for agriculture, as well as the future demand. Climate change is highly uncertain, but a warmer climate is already associated with changes to temperature and precipitation, and hence growing conditions for dryland agriculture, while changing patterns of snow accumulation and melt in the Rocky Mountains are changing the river flows that supply most of Canada's irrigated agriculture. A warming climate is expected to change both average growing conditions and extremes (as discussed in Chapter 2). Recent research has emphasized the increased risk of major drought in the Prairies, but increased flood risk is also expected to affect growing conditions and agricultural water management (Chapters 2 and 4). Demand for water resources is expected to increase due to economic growth, population growth, increased demand for water-intensive food, and other factors.

Water stress is expected to increase as expanding demand leads to more competition with the environment (discussed throughout Chapters 2 to 4). Competition for water resources between users is also expected to increase in many areas of the country (see Chapter 3). Further details on the challenges associated with predicting the future state of water resources are given in the Panel's response to Sub-Question 2.

Sub-Question 2

What more do we need to know regarding the water cycle and utilization of water in order to understand the adequacy and value of water supply in rural areas?

In the course of its deliberations and research, the Panel found that knowledge, data, and analysis of the water cycle and water usage in Canada are limited in a number of key areas. These limitations are inhibiting the ability of policy-makers and other stakeholders to understand the adequacy and value of the water supply, which, in turn, affects their ability to guide sustainable management of water for agriculture. Some priority areas of research for overcoming these limitations are described below.

Developing a Better Knowledge Base on the State of Water Resources

As explained in the Panel's response to Sub-Question 1, Canada lacks sufficient information about current water resources (including information about both water quantity and water quality). This makes it difficult to understand the impact of agriculture and other sectors, the nature of ongoing environmental changes, and the relative costs and benefits of various water management decisions, as well as those of different management practices, technological innovations, and governance strategies.

Each specific watershed and agricultural locale is distinct in many ways. There are differences in hydrology, climate, soil, and agricultural production, each of which affects the nature of the water resources, the agricultural possibilities, and optimal management strategies. In addition, many environmental changes take place on different time scales. Some changes, such as fluctuations in river water pollution levels, may take place by the hour; others, such as the migration of nutrient contamination into groundwater sources, can take decades. For these reasons, location-specific knowledge and relevant time-series data are needed to ensure effective, efficient approaches to sustainable management can be developed and implemented. In addition, data are needed for operational management of water resource systems, and for forecasting agricultural water needs at a range of time-scales. As discussed in the Panel's response to Sub-Question 4, improved monitoring resources and associated modelling can be part of the solution.

Assessing Risks and Uncertainties Affecting Future Water Availability and Quality

The future availability, usage, and quality of water will be affected by numerous factors, such as increased demands for food and other agricultural products (e.g., biofuels and bioindustrial products), competition from non-agricultural uses of water (e.g., industry, municipalities, hydro-electricity), the impact of climate change and variability, and others. To facilitate sustainable management, there is a need to develop a better understanding of these risks and uncertainties, as well as their impacts on specific watersheds and agricultural locales.

Insights into market demands, water futures, and competing uses can be developed through socio-economic research, foresight exercises, and scenario analysis. In countries such as the U.K. and Australia, targeted research in these areas is helping to inform policy- and decision-making in government, industry, and among other stakeholders. Canada could do more to invest in these forms of research, collaboration, and analysis. Faced with high uncertainty concerning water futures, including uncertain effects of climate change, new approaches are needed to adaptive management, focusing on strategies that are robust rather than optimal (Lempert & Schlesinger, 2000).

Understanding the impact of factors such as climate variability and climate change requires additional knowledge, information, and analysis about global changes, local conditions, and their interactions. These issues are particularly complex in Canada, where a warming climate is changing patterns of snow accumulation and melt, with effects on river flows and agricultural land management. Of particular concern is the prospect of increased frequency of floods and drought (Bonsal *et al.*, 2012). Floods and multi-year droughts have been a recurring characteristic of the 20th century observational records for the Prairies, with high economic costs (Wheaton, 2011), yet longer duration droughts have been seen in paleo-records. While Canadian agriculture has adapted successfully to extreme climate variability, further adaptation is likely to be needed, and further consideration of the role of agriculture in mitigating their wider effects. This could include, for example, the role of agricultural drainage and wetland conservation in promoting drought resilience and mitigating downstream flood risk, and the potential role for agricultural land to provide floodplain storage in extreme events. Developing these possibilities calls for pilot sub-watershed study sites where these issues can be investigated in natural settings and at an integrated scale. Other important areas of research include the influence of climatic variability on potential demand for irrigation and drainage, on nutrient loads and their effects on aquatic ecosystems and drinking water quality, and on the fate and occurrence of pathogenic species in groundwater (see Chapter 3 for further discussion of these and other research needs pertaining to risks and uncertainties). Clearly, improvements in international and national climate science related to reducing uncertainty in climate scenarios, and improved short-, medium- and long-range forecasts, would be of major benefit.

Managing Agriculture's Relationship to the Water Environment

In some of the world's most advanced economies, there is growing recognition of the importance and complexity of agriculture's relationship to the water environment. The issue of nutrient loadings in the environment is one such example. In the U.S., the EPA has noted that anthropogenic creation of reactive nitrogen provides essential benefits for humans — first and foremost in meeting human dietary needs. However, it goes on to explain that agriculture uses more reactive nitrogen and is responsible for more reactive nitrogen losses to the environment than any other economic sector. In fact, according to its calculations pertaining to Chesapeake Bay alone, "…direct additions to the environment from agriculture are about 370,000 tonnes of reactive nitrogen per year and cause $1.7 billion worth of damage" (U.S. EPA, 2011).

As outlined in Chapter 4, agricultural land use practices have quantifiable, deleterious impacts on the water environment in Canada. Although the impacts are clear, their implications for the long-term sustainability of agricultural practices across the Canadian landscape are largely unknown as a result of insufficient data and in-field research. Comprehensive assessments of phosphorus contamination in surface waters and nitrate pollution in groundwater are needed. Preserving the required quantity and quality of the water resources in agricultural settings will require additional research and data collection with a specific emphasis on the documentation of the performance of BMPs designed to minimize environmental impacts of agricultural activities. Research opportunities and priorities pertaining to BMPs are further addressed in the Panel's response to Sub-Question 3.

Conservation Agriculture and Ecosystem Services Approaches

As part of efforts to better guide sustainable management of water for agriculture, the Panel observes that there is also an opportunity to reshape our approach to the role of agriculture and its benefits. As discussed in Section 4.4 and Sub-Question 3, one approach is conservation agriculture, which seeks to enhance diversity of production to achieve greater robustness and resilience to change, in many respects building on BMPs. A second, related approach considers that this can be accomplished through a shift in thinking about agriculture and farmers as places and people that produce food products to places and people that sustain and maintain landscapes that provide a great many important services. The Panel believes that such a shift is critical to maintaining Canada as a leader in global agriculture; however, encouraging this shift will require further research in a number of areas related to ecosystem services and the environment, particularly those aimed at helping to understand effects of management decisions on multiple ecosystem services, including biodiversity and habitat (Bennett *et al.*, 2009).

The value of the ecological goods and services associated with surface waters within the agricultural landscape, while not well understood, is becoming a topic of international concern. The value that society places on wetland regions, wildlife habitat, and species diversity, for example, is becoming an important factor in the long-term management of watershed systems. The enhanced drainage of agricultural lands can significantly influence these aspects, yet a sufficient, science-based understanding of many of the key controlling processes required to manage agricultural drainage in a sustainable way, including potential for local and regional flood risk mitigation, is lacking (see Chapter 4).

Society will need to evaluate and prioritize the objectives it most wants to achieve. As discussed above, this requires a better understanding of the water cycle and environmental needs, together with an understanding of the current and future usage of water, to create a sound scientific basis for evaluating the trade-offs involved. Furthermore, as outlined in Chapter 6 and in the Panel's response to Sub-Question 5, socio-economic information, analysis, and tools are also needed to assist with valuing water, influencing behaviours, and engaging stakeholders to adjudicate among competing uses and interests.

Sub-Question 3

What additional knowledge is required to understand sustainable practices and possible adverse effects related to use of water in rural areas?

Sustainable approaches can contribute to maintaining healthy ecosystems by minimizing the environmental impact of agricultural production. In this respect, the Panel has focused on conservation agriculture and BMPs; technological opportunities and research and development priorities; and stakeholder engagement strategies (and other governance strategies and policy tools). The main research priorities the Panel has identified for each area are described below.

Conservation Agriculture and BMPs

The Panel acknowledges the fundamental value in the conservation agriculture approach to providing farming systems that are inherently more resilient and have a greater potential for resource use efficiency and productivity, in particular when developed as a platform for the application of BMPs and advanced agricultural technologies. The Panel believes there could be considerable opportunities for Canada to further develop and leverage its expertise in these areas.

BMPs are cost-effective, practical methods that minimize the environmental impacts of economic activities such as agricultural production, and they are an important dimension of conservation agriculture. There are a variety of BMPs that can contribute to the sustainability of agriculture and its environment by improving water use efficiency or protecting water quality, for example. Types of BMPs include riparian buffer strips, crop rotation, wetland restoration, reduced tillage, on-farm water storage, and controlled tile drainage (see Chapter 4). Conservation agriculture and BMPs have excellent potential for improving sustainability; however, they need to be carefully explored to assess effectiveness and practicality. In particular, there is a need for the assessment of the potential cumulative effects at a regional scale. A key policy question is the extent to which BMPs can deliver outcomes that are consistent with desired environmental values.

Some key research questions are:

- What are the demonstrated, quantifiable environmental benefits of the system or practice?
- What are the best ways to measure impacts on biodiversity and ecosystem services?
- What are the economic costs and benefits? Who bears what costs (e.g., farmers, government) and who receives which benefits (e.g., farmers, rural communities, Canadian society)?
- What are the social factors affecting adoption (e.g., perceptions of benefits, education levels, farm size, sources of income)?
- What are the most effective governance strategies and policy tools for promoting adoption?

Related issues of specific concern include:

- the local and regional impacts of changing cropping and tillage practices on runoff processes and water quality;
- the role of agricultural drainage and loss of wetlands on flood risk, drought resilience, water quality, and habitat, at local and regional scales; and
- the potential effects of BMPs on nutrient loads to surface water and groundwater systems.

Additional scientific knowledge is required across the full range of these considerations, as are more transdisciplinary integration of knowledge and a better understanding of how such knowledge can be best applied to specific local conditions. This includes research to examine the efficacy of industry and third-party certification standards related to conservation agriculture systems and BMPs. However, an overriding unresolved question is the extent to which cumulative impacts of these improved practices can achieve desired environmental objectives.

Technological Opportunities

Current and future technologies offer significant opportunities for improving water use efficiency and environmental protection, while increasing the output and productivity of the agricultural sector (Beddington, 2010; Godfray *et al.*, 2010; Jaggard *et al.*, 2010; Piesse & Thirtle, 2010). These opportunities are spread across a range of technologies, including irrigation technologies; water harvesting; genetically enhanced seeds, plants with novel traits, and other biotechnologies; reduced risk pesticides; and precision agriculture technologies (see Chapter 5). In addition, improved forecasting of climate, water resources, water quality, and water demand can offer significant improvements in efficiency of water resource utilization and agricultural water management.

Some important overarching research questions in these areas are:

- What technologies offer the greatest potential economic and environmental benefits for Canadian agriculture? How are those benefits distributed, relative to costs, among different stakeholders (e.g., farmers, rural communities, Canadian society)?
- What are the current technologies that offer the greatest promise to deliver immediate benefits for Canadian agriculture? What are the best governance strategies and policy tools to encourage adoption of these technologies among agricultural producers?
- What are the main areas for future investment in research and development that can offer the greatest potential benefits for the Canadian agriculture sector? What are the best governance strategies and policy tools for encouraging this investment?

As in the case of BMP research opportunities, these technological research opportunities need to be examined in the context of specific watersheds, agricultural conditions, and product types. Given the wide variation in these parameters of agricultural production in specific locales, there can be no blanket solutions that will be appropriate for all types of farms and geographic areas. What can be developed, however, is a suite of tools that can be adopted, adapted, and applied by local producers and other stakeholders.

In addition to the overarching research questions, the Panel also identified several more specific research needs relating to particular technologies. Some examples include:

- updating our knowledge about the ways in which advanced irrigation technologies and techniques might be applied in Canadian contexts;
- consolidating our knowledge of on-farm wastewater treatment methods;
- supporting Canadian efforts to develop new genetically enhanced seeds, plants with novel traits, and other biotechnologies, including varieties and cultivars that require less water and are more resistant to water stress, and possess greater disease tolerance/resistance and higher nutrient efficiency;
- examining the potential costs and benefits of encouraging increased adoption of specific "smart-field" technologies such as field sensors (e.g., soil moisture), wireless environmental sensor networks for real-time decision making (Díaz *et al.*, 2011; Zerger *et al.*, 2010), variable rate applicators (VRA) for agrochemicals/pesticides, fertilizers, solid and liquid manures and other biological wastes (e.g., sewage sludge biosolids), remote sensing, and geographic information systems (GIS) (Roblin & Barrow, 2000); and
- establishing demonstration projects and providing extension services to encourage and increase deployment of research outputs and technologies.

Policy Tools and Stakeholder Engagement Strategies

Development of BMPs and technological opportunities must be accompanied by effective policy tools and strategies for engaging stakeholders in the uptake of such opportunities. Sustainable management of water for agriculture depends on the participation of stakeholders or their sense of responsibility in a given environment (local, region, and basin) (Cosgrove & Rijsberman, 2000b). In addition, agricultural producers, rural communities, provincial and federal governments, and other stakeholders each have important information and insights that can help to shape the nature of the BMPs and technologies adopted in a given area, and support the effectiveness of their application.

The response to this sub-question focuses on knowledge transfer and stakeholder engagement. Other governance strategies and policy tools for encouraging sustainable practices are discussed in the Panel's response to Sub-Question 5.

The Panel maintains that it is important to understand that stakeholder engagement goes beyond simple diffusion of information to encouraging an active dialogue that involves sharing information and responsibilities. Supporting this dialogue calls for additional research on the following questions:

- What are the best techniques for considering the relative economic, environmental, and social values of water resources?

- What policy tools are most appropriate for ensuring these values are reflected in how water is used (in various economic, political, and social contexts)?
- What are the most effective social learning strategies that can be applied to improving the sustainability of the Canadian agriculture sector?
- What forms of knowledge transfer and exchange have proven effective in other countries? How might such approaches be adapted to specific local contexts in Canada?
- What is the potential for employing social media and other new forms of media for engaging stakeholders in dialogue about sustainability and in the uptake of sustainable practices?

The Panel recognizes that stakeholder engagement strategies need to be adapted to specific objectives and audiences. However, it suggests that a better understanding of which methods have the potential to be most effective is an important first step in developing a range of tools and techniques that can be adapted and applied in different watersheds and rural communities across Canada.

Sub-Question 4

What additional knowledge and monitoring practices are required in order to make progress on gathering and using bio-physical information to optimize the use of water?

For this sub-question, the Panel interpreted “bio-physical” information to mean data and knowledge pertaining to the biological and physical environment (e.g., vegetation and wetlands, wildlife, hydrology, soil conditions, and land use). Additional knowledge and monitoring are needed to make progress on gathering and using bio-physical information to optimize the use of water. Improvements in the collection of monitoring data on water quantity, quality, and environmental flows (including the meteorological drivers), as well as enhanced scientific capacity to analyze and use such information, are among the areas that can contribute to more effective sustainable management of water for agriculture. Given resource constraints, the Panel believes this data gathering and knowledge development should be targeted to specific areas of concern on a risk-based basis. It also thinks that research to determine the risk-based priorities is needed as an essential first step in this process.

Water Quantity Monitoring

Monitoring water available for agriculture includes assessing water stocks, water flows, and water usage, and the changing patterns of water availability arising from climate variability and change. This requires a wide variety of ground-based and remotely-sensed data, and modelling. These monitoring data to define water availability and use are adequate in some agricultural areas, but inadequate in many other places, particularly in less populous areas (see Section 3.3). In addition, monitoring provides the essential data for models used to support operational land and water management. Improved modelling and forecasting can provide significant opportunities in terms of both improved water resources management and on-farm water use.

Water Quality Monitoring

The quality of water resources can be assessed based on physical, chemical, biological, or other parameters, each of which can vary greatly in space and time due to natural processes and human impacts. Consequently, the analysis of such parameters can be costly and time consuming. As a result, national data sets can be very limited in terms of both the spatial networks available and the temporal resolution of sampling. In Canada, the Auditor General's Office and other organizations has found that the lack of consistent water quality monitoring arrangements across the country impedes the ability to share costs across jurisdictions, exchange information and expertise, and compare data from across the country (Auditor General of Canada, 2010; CCME, 2006). The Panel observes that particular issues arise concerning:

- nitrate and phosphorus — current information is inadequate to define the national extent of the problem, the specific local effects of BMPs, and their potential regional impacts;
- pathogens, and the associated risks of groundwater pollution; and
- more generally, the lack of information on groundwater quality, which hampers both risk assessment and management.

The Case for Improved Monitoring of Water Quantity and Water Quality

Effective water monitoring is critical to sustainably managing water. Water resources across Canada are under pressure from urban development, industrial activities, agriculture, hydropower and thermal energy production, and other factors, not the least of which is environmental change (Auditor General of Canada, 2010). Information on water quantity and quality allows timely identification of emerging threats, while inadequate or insufficient information could necessitate expensive remediation efforts that could have been avoided (Auditor General of Canada, 2010). To identify such threats, however, monitoring data across a range of spatial scales must be assessed and evaluated to determine cause-and-effect relationships.

This includes the small catchments appropriate to monitor impacts of agricultural practices, including BMPs. This analysis must also be published and disseminated to promote understanding of existing conditions, trends, and potential risks to support effective policy development and environmental management (Alberta Environmental Monitoring Panel, 2011; CCME, 2006). Of particular concern are the risks of changing climate on Canada's agriculture and water resources. These include changing patterns of rain and snow, changing temperatures and growing seasons, changing river flows, and the prospect of increased floods and droughts.

The Case for Predictive Water Modelling in Canada

Not all streamflow, lake level, groundwater, and water quality parameters can be measured at the full range of scales; therefore, water measurement must be supplemented by the modelling of water quantity and quality for ungauged basins and ungaugable situations (Sivapalan *et al.*, 2003). Models can also play an important role in the exploration of future conditions, which by definition cannot be measured. They can be a valuable guide to planning and management; for example, by simulating the potential effects of different management strategies.

Implications of Monitoring and Modelling for Agricultural Water Management: Supporting Adaptive Management

Agriculture is concerned with monitoring, modelling and other methods of managing the risks associated with agricultural production. The Panel notes with respect to river basin modelling that some, but not all, provinces have modelling capabilities for water supply prediction and management and flood forecasting, and that there is no regular operational water quality modelling in Canada. The Panel also notes that the complexities of cold region hydrology pose significant challenges for simulation of both hydrology and water quality, and that there was a particular need to improve the capability to represent the effects of agricultural management, including BMPs.

Both strong monitoring and strong modelling are needed to manage agricultural risk in a time of non-stationarity. In a report on the effects of climate warming on hydrologic extremes, the U.S. National Academy of Sciences (NAS) suggests "Basic monitoring of key elements of the hydrologic cycle provides an irreplaceable information resource that is particularly critical in a non-stationary environment" (NAS, 2011). Though the NAS report emphasizes the need for a strong observational network for meteorology and water, it warns that this should not replace advances in forecasting: "reliance on observations-based, *a posteriori* analysis — although practical in the short-term — may obscure the inherent value of research aimed at causality and improved forecasting." The Panel observes that Canadian monitoring and forecasting capability is not as advanced as that in the U.S., and believes that the development of an improved coupled monitoring and forecasting capability in Canada would provide for better risk management in agriculture in light of unprecedented hydrometeorological non-stationarity due to climate change.

Provision of improved estimates of the probabilities of extreme hydrometeorological events and water supply can aid in adaptive management of agricultural activities and in the design of improved water management techniques for Canadian application. This will be particularly important as non-stationarity due to climate change causes significant uncertainties for global agriculture (Nelson *et al.*, 2010). Adaptive management will be needed for Canadian agriculture due to greater extremes of flood and drought under climate change, and to changing hydrometeorological conditions of less snowfall and snowmelt runoff. Increasing interannual variations in hydrometeorological conditions will require that agricultural land managers and other stakeholders have a wide range of management techniques available to them that can be deployed with as little notice as possible (Pahl-Wostl, 2007; UNESCO, 2012). Expanded diversity of management on the farm may also be important in the resiliency of agricultural production in the face of high predictive uncertainty and hydrometeorological non-stationarity.

The Need for Better Understanding of Terrestrial and Aquatic Habitats and Environmental Flows

Understanding the effects of changing water quantity and quality on ecosystems is another important area in which increased knowledge could contribute to sustainable management. This applies in general to the quantification of potential contributions from agriculture to ecosystem services. More specifically, detailed, quantitative, synthetic knowledge of environmental flows of water needed to preserve habitat and maintain biodiversity in Canada is quite slim. While there is a general understanding that attempts to maximize agricultural production without considering the environmental consequences can cause declines in biodiversity and ecosystem services, understanding of the interactions among these services and how these interactions can be exploited to reduce trade-offs and increase synergies is extremely limited (Bennett *et al.*, 2009). For example, there is no quantitative understanding of the flows (timing, amount, and quantity) needed to maintain biodiversity and habitat across a broad range of ecosystems in Canada. While there have been excellent and detailed studies in particular locations, a synthesis of this across regions, cropping systems, and management regimes, does not exist (Bennett *et al.*, 2009). This leads to a host of sub-questions about habitat, biodiversity, and agricultural water management. For example, is the relationship between water flow and aquatic habitat a linear one or is it a relationship with thresholds and non-linearities? If it is the latter, the question is what are the critical levels of flow beyond which we cross thresholds for various organisms?

Sub-Question 5

What additional socio-economic and environmental information and analysis needs to be considered for the sustainable management of water in rural areas?

Practising and Enabling Effective Governance

Based on its research and deliberation, the Panel concludes that effective governance is an essential prerequisite to sustainable water management in agriculture. Water governance in Canada is highly fragmented, with multiple levels of government holding or sharing responsibility. Contemporary water governance processes in Canada are diverse and include traditional regulatory approaches, collaborative processes, market-based processes — and combinations of all of these. The roles of non-government actors, indigenous peoples, civil society groups, and businesses are increasing and changing relative to previous decades. Consequently, a host of new challenges exist relating to effectiveness, capacity, legitimacy and accountability. Understanding of how best to address these challenges is uneven. Importantly, there is no "one-size-fits-all" framework for improving governance that will work in all jurisdictions. Thus, the Panel focused on principles and promising practices that have been shown to be effective for supporting sustainable water management.

Ensuring governance operates at the appropriate scale. Water resources do not conform to municipal, provincial, or national boundaries, and decisions by those operating at one level or location can affect others. Watersheds can offer a useful focus for coordinating decisions and actions; by managing resources at this level, the integration of management efforts and knowledge is possible, leading to more effective governance of water resources (Section 6.1).

Integrating land-use planning with water management decisions. Land use and water management are interconnected, as decisions related to one will affect the other. Agriculture can affect both water quantity and water quality in a given watershed, while other land use decisions, such as natural resource development or building a hydroelectric dam, will have an impact on the availability of water for other uses such as irrigation. Integrating land use and water management decisions can help to ensure the best possible outcomes for the most stakeholders while limiting the impact of the decisions on the environment, economy, and society. Overall, effective integrated water management strategies will take into account the needs of agriculture as well as other uses, while ensuring sustainable water management in the long run (Section 6.1).

Involving affected stakeholders in decision-making. Water management decisions affect the lives of people living within watersheds in many ways, and often involve trade-offs between competing uses. It is important to consider the views and concerns of relevant stakeholders inside and outside the agricultural sector when making water management decisions related to farming. Similarly, it is also essential to include the public in the decision-making process (Section 6.3). While the type of collaboration and the tools for incorporating participation must be based on the local situation, there are a range of possibilities that can be adapted to meet various conditions. To be effective, the knowledge transfer strategies used must be chosen based on the type of information to be communicated, the intended audience, and the associated objectives. Additional research into knowledge transfer strategies, as they relate to agriculture and water use, is needed to improve the effectiveness of communication between government and relevant stakeholders. See Section 6.3 and the Panel's response to Sub-Question 3 for additional details.

Incorporating knowledge into the decision-making process. Scientific information is a tool that should be used to help policy-makers and stakeholders understand the benefits and trade-offs of a given decision. In addition, science can be employed as a tool for informing governments and the public about the costs of doing nothing. Scientific input needs to be grounded in strong data and analysis and must be seriously considered by policy-makers in the decision-making process (Section 6.1). The Panel noted the use of foresight studies by the U.K. and other governments as a tool for informing research and policy priorities (Section 3.6). It believes that use of such tools should include some consideration of potential responses to major catastrophic events (e.g., severe droughts, extreme weather) so as to be better prepared for significant issues, should these arise. In addition to scientific knowledge, effective water management and governance requires insights derived from applied expertise, indigenous knowledge, and local knowledge. Integration of scientific and other forms of knowledge in decision-making processes can lead to more robust solutions that account more effectively for the complex and interconnected nature of current water management and governance challenges. Transdisciplinary research, where researchers and partners from the farm community, industry, and government jointly define problems and research programs, is an important way to facilitate knowledge co-production.

Economic Instruments to Support Sustainable Water Management

Agricultural policy strongly influences stakeholder decisions that affect water use in agriculture. Agricultural policy often strives to ensure the sector is economically competitive, while also addressing relevant environmental and social concerns. Experiences from across Canada and around the world demonstrate that economic instruments — when designed properly and implemented appropriately — can support the goal of sustainable water management. The Panel considered the potential for economic valuation techniques, economic incentives, pricing, and water markets to contribute to sustainable management of water for agriculture. Investigation of how these tools can be used effectively in the Canadian context is needed, as are mechanisms to measure their success.

Economic valuation techniques. Water has economic, environmental, and social values that must be considered when making water management decisions. One method for assessing the value of the ecosystems supported by water resources is determining the total economic valuation (TEV) for ecosystem services. Both the use (e.g., irrigation, drinking water) and non-use (e.g., biodiversity, cultural heritage) values of water are included in a TEV approach.

Economic incentives are another mechanism that can be used to help shape behaviour to preserve the quantity and quality of water resources. Examples of economic incentive tools include payments for voluntary adoption of BMPs, payments for ecological services (PES), pricing signals, and tradable water rights markets. These tools each have advantages and drawbacks that should be taken into account when trying to achieve particular goals. The Panel concludes that research is needed to determine how economic incentives can be used to help achieve sustainable water management in the context of Canadian agriculture.

Pricing is a market mechanism that can promote sustainable behaviours by creating economic incentives for improved water management practices. In the context of drinking water systems, raising the price of water to reflect its total value and the full cost of providing water services is thought to be one way of promoting more efficient use of water resources. The Panel concludes that significant questions exist about the ability of individual farmers to pay a higher price for water, and noted that experiences from urban drinking water systems may not translate well to agriculture.

Water markets, where rights to access water are traded, are another mechanism that can be used to promote efficient use of water resources. Water markets permit shifting water from low- value to high-value sectors — sometimes within the agricultural sector, but often from agricultural to non-agricultural uses. Numerous mechanisms have been developed for both the temporary and permanent transfer of water using economic tools. Water markets exist in several countries around the world, including Canada (where they are used in Alberta to facilitate the temporary or permanent transfer of rights to use water). As with other policy tools, there are concerns and obstacles associated with market mechanisms. These include public unease about the commodification of water, and questions about the ability of markets to provide for non-market environmental needs. The Panel also notes that the pre-conditions needed to establish water markets do not exist in many parts of Canada.

7.3 FINAL THOUGHTS

Managing water sustainably is essential for the future of the Canadian agriculture sector and for Canadian society. Water is a critical input not only for agricultural production, but also for many other economic and social activities, and — most importantly — for the health of the environment. As the world's population and incomes continue to grow, demands for increased agricultural production will rise. These developments will place rising pressures on water, land, and other resources, both in Canada and abroad, putting agriculture in competition for these resources with municipalities, industries, and the environment. A major challenge is that these pressures are set against a context of changing climate, with high levels of associated uncertainty. Meeting these challenges will require agriculture and other industries to produce more food and other products with less water, less land, and less impact on the environment per unit of output. It will also require new solutions to policy, governance, and management to provide robust and resilient futures for water and agriculture.

In this report, the Panel has identified numerous options for agricultural producers, policy-makers, and stakeholders to make progress in better guiding the sustainable management of water for agriculture. Foresight research on opportunities, risks, and uncertainties; implementation of BMPs; development of technological innovations; and the use of governance strategies and policy tools can all contribute to this endeavour. Decision-makers will need to adapt and apply these options to their particular sub-sectors, watersheds, landscapes, regulatory regimes, and other local conditions. These necessary changes will require additional research, collaboration among stakeholders, time, and investments. It will also require a coordinated effort by all stakeholders in their areas of responsibilities. For the Canadian agriculture sector to remain competitive and resilient in the future, it is essential for such efforts to begin now to ensure that it can remain a world leader in productivity and innovation, as well as an important contributor to Canada's economic growth and food security.

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