



Ontario Genomics

Genomics for Agriculture & Agri-Food:

Ontario's Strategic Opportunity

Genomics Strategy Report for the
Ontario Agriculture & Agri-Food Sector

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1. Executive Summary

Ontario's agriculture and agri-food (AAF) sector is large and diverse with abundant natural resources, including more than half of Canada's Class 1 farmland, two of the country's best agroclimatic zones, and abundant water. The sector ranges from input and service providers, to highly diversified primary crop and livestock production, to the manufacture of food products and industrial bioproducts for domestic and export markets, as well as transportation and distribution, including retail and food service providers.

Genomics has played, and will increasingly play, an important role in contributing to the advancement of the global AAF sector. This document describes the many and varied contributions that genomics can make to the sector. It is focused through the lens of Ontario's dynamic and highly diverse AAF sector. It is set in the context of enhancing a sustainable AAF system that produces high-quality food and feed as well as industrial bioproducts, using farming and processing technologies that contribute to Ontario's and Canada's economic development, protects the environment, helps to mitigate and adapt to climate change, and promotes human health and wellness and animal welfare.

To support a socially and environmentally responsible industry, we look at contributions that genomics can make to crop and livestock production and protection, to healthier soils and an understanding of the microbial communities that are essential for this, to food and beverage manufacturing, and to the development of the bioeconomy. We consider the links of the AAF sector to other natural resource sectors, the role genomics can play in helping to understand and preserve biodiversity, and the opportunities to contribute to global food security.

The rapid decline in sequencing costs in recent years and the large number of novel scientific advances becoming available are providing powerful tools for understanding metabolism and altering it through changes in gene expression and regulation. Applied genomics and systems biology approaches can be used to integrate knowledge from diverse biological components and data into models of the system as a whole.

Rapid advances will be made worldwide in genomics research and its applications, using existing knowledge along with innovations and technologies that cannot be fully anticipated at this time. Ontario, with its abundant human and natural resources, its diversified economy, and its stable institutions and political systems, has the current capacity and potential to be a significant participant, and even a leader, in some areas concerned with advances in genomics research and its applications to the AAF sector.

Building on Ontario's strengths and opportunities, the following constitute rich domains for Ontario to make advances in genomics research and innovation to advance the AAF sector:

1. Augment multidisciplinary R&D using a systems biology approach, with a focus on increased understanding of microbiomes and their interconnectivity to human health.
2. Prioritize programs for sustainable agriculture and food that consider the economy, the environment, and society, for crop production and livestock.
3. Enhance advanced manufacturing and processing systems for both food and industrial bioproducts, including fermentation and traceability.
4. Develop rapid diagnostic methods to support regulation and trade, rapid disease detection and traceability in crops and livestock, and biologics to reduce the use of antimicrobials.
5. Address barriers to the adoption of genomics innovations including issues related to data sharing, intellectual property, regulation and public acceptance.
6. Leverage Ontario's strengths in computational biology and artificial intelligence to accelerate the development and application of agricultural genomics-based innovations.

2. Introduction

A hundred years ago, over half of Canadians worked on farms, although today it is less than two percent of the population.¹ Although a much smaller proportion of the workforce is directly involved in primary agriculture today, the Canadian agriculture and agri-food sector (AAF) in its entirety is large, comprising 6.7% of Canada's total GDP and providing one out of eight jobs.² The diverse and large Ontario AAF sector accounts for one-third of the total Canadian AAF GDP (\$37.6 billion in 2016).^{3,4}

Agriculture and food production represent not just important contributions to Ontario's economy, but also represent an important cultural component that directly impacts our health and wellness. In 2017, the Government of Canada began the development of "A Food Policy for Canada" focusing on increasing access to affordable food; improving health and food safety; conserving our soil, water, and air; and producing more high-quality food.⁵

Nationally, the Government of Canada's 2017 budget⁶ responding to advice from the Advisory Council on Economic Growth⁷ has set a target for the AAF sector to achieve, by 2025, annual agri-food exports of at least \$75 billion, an increase from \$56 billion in 2016.⁸ The Ontario AAF sector will play an important role in achieving this objective. In its recent budgets the Government of Canada has committed to increasing investments in science and technology, including the AAF sector.

Ontario is also well positioned to develop a strong bioproducts sector that would be focused on nonfood uses for agricultural products, including fuels, biomaterials, fine chemicals, and pharmaceuticals.⁹

There is an ongoing challenge to improve our ability to ensure that Canadians can have access to a nutritionally balanced and varied diet based on domestic supply, to enable more import replacements, and to increase sector profitability through more sustainable production systems and further product diversification. This will all need to be done while the sector is adopting measures to mitigate and adapt to the impacts of climate change.

AAF genomics is concerned with understanding biological systems and ecosystems relevant to agriculture and food, and using this knowledge to obtain scientifically, economically, environmentally, and socially desirable outcomes. In the context of the AAF sector, it applies to crops and livestock, beneficial and harmful microorganisms, insects, and other organisms that are part of complex agroecosystems or part of processing systems that interact with one another, often in complex and relatively poorly understood ways.

Genomics, in the narrow sense, is concerned with genetic mapping and DNA sequencing of sets of genes or the complete genomes of organisms, organizing this information in databases, and applying of these data to biological systems; however, for the purposes of this strategy, this is too limited a scope. Consistent with Ontario Genomics' mandate, this strategy document embraces the whole array of cellular processes ("-omics") related to transcription, translation, posttranslational modification, regulation, and expression (Figure 1). These include, but are not limited to, functional genomics, transcriptomics, proteomics, metabolomics, epigenomics, metagenomics, and phenomics, which will collectively, for the purposes of this document, be referred to as "genomics."¹⁰

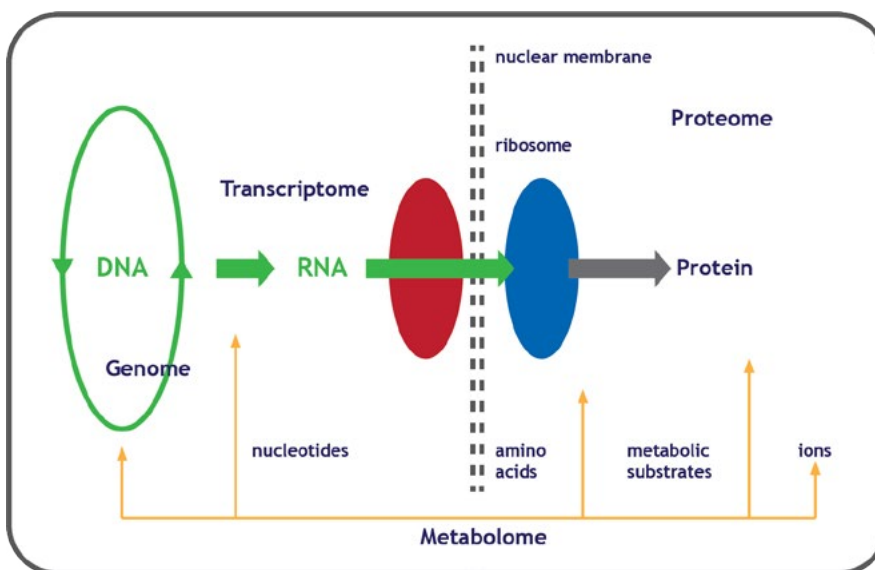


Figure 1 – A generalized eukaryotic cell showing connections among the genome, the transcriptome (the messenger RNA molecules expressed from the genes of an organism), proteome (the complement of proteins that is or can be expressed) and the metabolome (the total number of metabolites present).

Increasingly, AAF genomics will be inextricably linked with such advances as next-generation sequencing (NGS),¹¹ gene editing, synthetic biology,¹² artificial intelligence, machine learning, and precision agriculture. New tools and methods and new approaches will provide quantum leaps in our understanding of complex biological systems from the molecular and biochemical levels to the ecosystems level, and they will be applied to a whole array of production and processing systems, including conventional production systems, organic farming systems, and natural products production.

This sector strategy is focused on the role that genomics can play in helping the Ontario AAF sector excel. It is aimed at a diverse group of stakeholders—academia, government, industry, civil society—highlighting opportunities where genomics can help the sector innovate, adapt, and compete. It is intended to help provide guidance to government and industry stakeholders investing in genomics-based innovations in Ontario. It will also contribute to the National Genomics AAF strategy being developed by Genome Canada, the six regional Genome Centres across the country, Agriculture and Agri-Food Canada (AAFC), the Natural Sciences and Engineering Research Council of Canada (NSERC), National Research Council of Canada (NRC), and the Canadian Food Inspection Agency (CFIA). In addition, there is a complementary National Genomics Fisheries and Aquaculture Sector strategy that is being developed by Genome Canada, the regional Genome Centres, and Fisheries and Oceans Canada (DFO).

This strategy also addresses citizen engagement. While applications of many genomics advances will be primarily of interest to scientists, regulators, and industry stakeholders, genomics research and its potential applications in the AAF sector will need to be addressed in the context of ethical and policy questions to determine whether there is the social license to apply them in practice.



3. Ontario's Contribution to the Canadian AAF Sector

3.1 Current Importance

The AAF sector in Ontario ranges from input and service providers, to primary crop and livestock production, to the manufacture of food products and industrial bioproducts for domestic and export markets, as well as transportation and distribution, including retail and food service providers. With more than 14 million residents (39% of Canada's population)¹³ and approximately 150 million consumers within a day's drive, the Ontario AAF sector has access to a large and diverse consumer base. This creates opportunities for producing commodities and manufacturing food and beverages with appeal to a wide range of ethnicities and lifestyles.

The Agricultural Institute of Canada (AIC) has recently published a comprehensive overview of the Canadian agricultural innovation system.¹⁴ Using 2015 data, Canada's expenditures in agricultural R&D and extension are about \$913 million (0.046% of GDP) and Ontario, at \$104.5 million, accounts for 24% of total provincial expenditures in agricultural R&D and extension (ca. 2.8% of Ontario's AAF sector GDP in 2015).

Ontario has 49,600 farms with a total area of 4.98 million hectares.¹⁵ With abundant natural resources, including more than half of Canada's Class 1 farmland, two of the country's best agroclimatic zones, and abundant water, Ontario's primary agricultural production is very diverse in its range of field and horticultural crops and livestock species, as shown in Appendix 2. In 2016, Ontario's \$12.7 billion in total farm cash receipts accounted for 21% of the Canadian total.¹⁶





Ontario leads the greenhouse vegetable sector, representing 69% of the total harvested area in Canada in 2015, with a farm gate value exceeding \$820 million.¹⁷ Ontario also has a very diverse specialty crops sector that includes a wide array of specialty vegetables, fruits and nuts, industrial crops, and field and grain crops.¹⁸ Despite some skepticism about its economic feasibility,¹⁹ there is a nascent interest in greenhouse strawberry production in the Essex County²⁰ that could be assisted through genomics research.

Ontario has the third largest food and beverage manufacturing sector in North America, with meat, dairy, and bakery manufacturing as the major industries. The sector generates \$41 billion in revenue, provides over 130,000 direct jobs, and exports \$7.6 billion in product annually.^{21,22}

In 2014, Ontario accounted for 33.3% of Canada's agriculture and food processing GDP and 33.5% of the combined workforce of the primary agriculture and food processing sectors in Canada.⁴ In 2016, the total AAF GDP was \$37.6 billion and was 5.9% of the provincial GDP.³ It employed over 807,000 people, with about 9.6% in primary agriculture, 11.7% in food and beverage manufacturing, and 78.7% in related areas such as food retail/wholesale, foodservice, and restaurants.²³

Additional information and statistics for Ontario's AAF sector and the relevance of genomics research to them are presented in Appendix 2.

3.2 Outlook

Ontario's AAF sector is positioned for significant growth²⁴ due to its growing population, access to abundant arable land and water, stable and well-established markets and political system, strong infrastructure, and educated workforce. Advanced technologies are being applied to the management of crop and livestock production and in food processing facilities at increasing rates. Artificial intelligence, big data analytics, 'omics, and gene editing technologies will reshape and accelerate the productivity of the sector.

In 2016, increases in farmland prices in Ontario slowed somewhat to a 4.4% increase²⁵ which strengthened the economic prospects of those who already own land, and negatively impacted those who wish to purchase more land or enter into farming for the first time. At the farm level, there are fewer farm operations, but those operations are growing in size.^{26,27} Overall, at the farm level, mid-sized farms are being replaced by larger-scale operations while limited amounts of production to meet unique consumer demands are being fulfilled by small-scale farm operations.²⁸



While demographic trends are posing a challenge as the producer population is aging, and a farm labour shortage is growing²⁹, advancements in technology can help offset some of these challenges by reducing “hands-on” labour requirements. Additionally, women, who have always been important for farm enterprises, are increasingly taking on leadership and entrepreneurial roles in the sector.^{30,31} Ontario is also highly diverse ethnically and the place of residence for 39% of Canada’s immigrants in 2016, with immigrants representing 46.1% of Toronto’s population.^{32,33} This creates opportunities for agricultural products and food manufacturing diversification to meet the varied preferences of a diverse population, along with opportunities for import replacements and export opportunities.

Other factors constitute both challenges and opportunities, such as the impact of international trade agreements (e.g., CETA, CPTPP, NAFTA)[†], fluctuations in currency exchange rates, changes in weather patterns—domestic and foreign—or changes in consumer demand. However, Ontario’s AAF sector has traditionally been resilient, overcoming challenges such as adverse weather, pests and diseases, and unfavourable markets and, as Ontario’s Agri-Food Growth Steering Committee has noted,³⁴ “... *the Committee is confident Ontario can build its competitive advantage as a long-term global leader in food production for domestic and international consumption. Taking advantage of opportunities through recent trade agreements...will support this work. Industry leadership, responsive government programming, and supportive regulatory reforms are critical to increasing the competitiveness of Ontario’s agri-food businesses....*”

Currently, Ontario is experiencing an increasing trade deficit in the AAF sector, with the growth in AAF imports outpacing exports (see Appendix 2, Figure 2). Innovations in genomics R&D and the application of these advances will play a key role in the advancement of the Ontario AAF sector, helping it to reduce or eliminate its agri-food trade deficit and continuing Ontario’s tradition of early adoption of technological advances going back to the establishment of the Ontario Veterinary College (OVC) in 1862³⁵ and the founding of the Ontario Agricultural College (OAC) in 1874.³⁶

[†] CETA: Canada-European Union Comprehensive Economic and Trade Agreement; CPTPP: Comprehensive and Progressive Agreement for Trans-Pacific Partnership; NAFTA: North American Free Trade Agreement.



4. Genomics R&D Contribution to Ontario's AAF Sector

The promise of genomics technologies is to improve the efficiency of crop and livestock development. 'Omics technologies also enable the analysis of unintended changes in new crop varieties and livestock breeds that can potentially arise in new cultivars of crops or breeds of animals, regardless of the techniques used to develop them (e.g., conventional crossbreeding, genetic engineering, or others).

Understanding trends in AAF producer adoption of new technology is fundamental to forecasting how genomics technologies should be best positioned to impact the AAF industry. The rapid advancement of the Ontario AAF industry is largely due to uptake of new technologies (e.g., new cultivars, vaccines, improved agronomic practices, advanced mechanization) by producers and processors. There is considerable opportunity for genomics technologies to enhance the sector; however, new biotechnology products can be a source of concern for developers and growers from the perspective of consumer perception and market acceptance. This has had a dampening effect on the introduction of some new products, even though the scientific rigour that went into their development and the quality of the regulatory review of their safety and efficacy has met a very high standard.

Communications to educate and engage the public about beneficial new technologies is essential to ensure both social acceptance and sector growth.

Ontario AAF producers have generally shown a willingness to adopt new biotechnologies (e.g., herbicide tolerant or insect resistant cultivars), provided they are accepted by consumers and the marketplace, and producers can be confident about their positive economic and environmental net benefits. There is also a concern in the sector about useful new technologies not becoming available due to adverse misperceptions of their risks and benefits.



4.1 Crops and Pollinators

Genomics R&D will provide new approaches to crop development to achieve results that have been the continuing goals of crop breeding and genetics since the 19th century, such as improved disease and pest resistance, improved resilience, increased yield, better agronomic performance, and improvements in quality traits and consumer appeal (Appendix 2).



For major Ontario field crops (e.g., soybean, corn, wheat), genomics is well established in product development, and plant breeding is now prediction based. For example, conventional breeding has been aided since the 1980s by marker-assisted selection. The public sector in Ontario has a strong history in field-crop cultivar development, and these cultivars are licensed to various domestic seed companies. Currently, development of new cultivars and traits in the major field crops is primarily done by large multinational companies with most research activities done in other countries. This provides opportunities for Ontario's AAF genomics innovations to be licensed to large foreign-based companies or to use these technologies to build or strengthen domestic capacity as appropriate and feasible.



The Canadian Shield™ from the National Hardy Rose Program at Vineland Research and Innovation Centre.

Most product development for new horticulture cultivars is done outside of Canada by a few multinational companies. There is considerable capacity for public sector horticultural genomics research in Ontario (such as the Vineland Research and Innovation Centre [VRIC]). The commercialization of new horticultural crop innovations in Ontario is currently limited, since Ontario's requirements for new horticultural cultivars are generally being met by suppliers elsewhere in Canada³⁷ or abroad. However, through world-leading institutions like the VRIC and the University of Guelph, for example, new fruit and vegetable cultivars have the potential to fundamentally change this sector. A great example is the University of Guelph (UofG) invention, Ontario-bred Guelph Millennium asparagus, a \$30 million crop grown on 1,380 hectares in 2017, which comprises 100% of new asparagus plantings in the province.³⁸ Initially developed by AAFC, VRIC in collaboration with the Vineland Growers Co-operative brought the Cold Snap™ Pear³⁹ to market. Another VRIC success is the Canadian Shield rose,⁴⁰ bred especially for our difficult climate and released to celebrate Canada's 150th anniversary. Genomics technologies will enable and accelerate the development

of locally adapted horticultural cultivars. The ability of Ontario growers to access germplasm developed in Ontario enhances the ability of the industry to successfully produce superior crops.

Ontario also has a well-established ornamentals production sector (Appendix 2). This is an area where research on genetic modifications of some ornamentals could be conducted and tested with somewhat less stringent regulatory oversight required than is the case for novel plants with greater potential implications for impact on human and animal health or the environment.

As noted in *The Future of Plant Breeding Oversight in Canada—Workshop Primer* that was prepared for an industry workshop held in Ottawa in May, 2017, commercialization of plants with novel traits is limited in Ontario, as it is elsewhere in Canada, and mostly involves one of two techniques (mutagenesis, recombinant DNA) falling under two input traits (insect resistance, herbicide tolerance) for a few crops (soybean, corn, canola).⁴¹ Genetically modified sugar beets and alfalfa (for animal feed) are also grown in Canada. This limited level of commercialization is not so much due to scientific and technical constraints as it is to business decisions, securing regulatory approvals, international trade considerations, and market acceptance.⁴² Generally, there has been good market acceptance of genetically modified soybean (grown in 11 countries), canola (grown in four countries), and corn (grown in 16 countries).⁴³ Ontario is the largest soybean producer in Canada, with its farmers seeding 1.1 million hectares in 2016 with genetically modified cultivars occupying almost two-thirds of this area. Ontario farmers also planted 850 thousand hectares of corn for grain in 2016, with genetically modified seed making up 83% of their total planted area of corn for grain.⁴⁴ Genetically modified disease-resistant potatoes and non-browning apples are approved for production in Canada, but are not yet sold in Canada.^{45,46} The Canadian-developed non-browning Arctic™ apples are currently being commercialized in the USA.⁴⁷

Various new technologies have been developed, mostly outside Canada, intended to improve and accelerate breeding efficiency, with emerging technologies like genome editing (e.g., CRISPR—important both for basic research and applications⁴⁸), synthetic biology, and targeted epigenetic modifications rapidly becoming available. It has been noted recently in a report prepared by the US National Academy of Sciences⁴⁹ that *“new molecular tools are further blurring the distinction between genetic modifications made with conventional breeding and those made with genetic engineering”* and that *“more progress in crop improvement could be brought about by using both conventional breeding and genetic engineering than by using either alone.”* It further notes that *“in addition to contributing to crop improvement, emerging -omics methods could provide a rational pathway . . . for assessing health and environmental effects of new crop varieties produced by conventional breeding and genetic engineering.”* These developments, which are currently underway worldwide, will need to be considered in the context of Ontario’s genomics strategy.



Photo: Amro Zayed

Pollinators, including honeybees, leafcutter bees, bumblebees, and other wild pollinators, are essential for agriculture, and there is increasing concern about negative impacts on pollinator populations and interest in the role that genomics can play in understanding and mitigating these impacts.⁵⁰ Genomics research in Canada on honeybees has focused on improving colony health and resilience, reducing the need to import queens, thereby guarding against the inadvertent introduction of Africanized bees.⁵¹



4.2 Livestock

New genomics tools and approaches will contribute to improved growth and performance, improved feed conversion, disease resistance, and to increased understanding of animal biology, microbiomes, and the immune system for livestock species. This, in turn, will lead to improved disease resilience and better disease management; however, there will be a continuing need for the foreseeable future to develop more effective vaccines, other novel biologics and antibiotics, and genomics will contribute to these advances, as well. These advances will also contribute to animal welfare, including that of commercial livestock and a range of companion animals (e.g., cats,⁵² dogs,⁵³ and horses⁵⁴) that are also the subjects of genomics research.

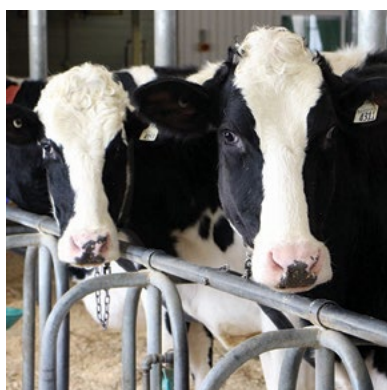


Photo: Ontario Veterinary College

A recent major success for the swine industry has been to demonstrate that by using gene editing pigs can be made resistant to Porcine Reproductive and Respiratory Syndrome (PRRS)⁵⁵ that's caused by a virus infection. A similar success has been reported for the African Swine Fever (ASF) virus,⁵⁶ a disease that is not present in Canada or the US but does represent a potential threat. These approaches to disease prevention contribute not only to improved production performance, but also to the animals' well-being. In addition to disease prevention, gene editing has been used to produce polled (hornless) Holstein (dairy) cattle,⁵⁷ an advance that, if approved for commercial production, would eliminate the need for dehorning, an unpleasant process both for the cattle and their handlers.

It would be premature to conclude that gene editing will be the most effective approach to manage all important viral diseases. With expertise and interest in Ontario in veterinary vaccine development,⁵⁸ this is an area that will benefit from genomics research and innovation. In addition, there is interest in biologics development at the NRC, providing excellent partnership opportunities.⁵⁹

Dr. Bonnie Mallard, a UofG researcher, has developed and patented the High Immune Response (HIR™)/Immunity+ technology, which can identify and select cattle with naturally optimized immune responses. Animals with the best immune response genes have about half the disease occurrence of average immune responders and better response to vaccination. Immunity+ technology has been marketed and sold by Semex, an Ontario-based global biotechnology company that specializes in dairy and beef genetics.⁶¹

The Enviropig™, a genetically modified line of Yorkshire pigs, with the capability to digest phytate-bound plant phosphorus more efficiently than conventional unmodified pigs, reducing feed costs and phosphorus pollution, was developed at UofG but, for reasons largely concerned with public acceptance, the project was terminated in 2012.⁶¹



A major concern for human and veterinary medicine relates to antimicrobial resistance (AMR) in pathogenic bacteria. The use of antimicrobial agents in veterinary medicine and livestock production raises serious concerns about their contribution to AMR in humans⁶² and animals. As noted in the workshop report of the Forum on Genomics and Antimicrobial Resistance⁶³, “...in 2014 the Canadian Animal Health Institute agreed to phase out the use of medically important antibiotics for growth promotion in livestock, and support increased veterinary oversight in therapeutic antimicrobial use,” noting further “that market pressure and accumulating scientific evidence will constrain the agri-food sector’s access to antibiotics in the future, and alternatives are going to be required”. Genomics can contribute to the development of effective alternatives that will include careful consideration of the health, safety, and well-being of livestock.

For example, improving the immune response of animals like pigs through microbiome manipulation could lead to reduction or elimination of antibiotic use at weaning into the nursery phase. Similarly, there is a need for studies of the impact of gut microflora on the nutrition, feed conversion, pathogen carriage, and health of poultry in an antimicrobial-free environment. Genomics approaches, such as genome editing, could be used to develop ways to immunize broiler chickens against necrotic enteritis and contribute to a better understanding of the biology of avian influenza virus, as well as new ways to control enteric pathogens.⁶⁴



One of the main barriers to reducing antimicrobial use has been the lack of rapid “chute-side” diagnostics for producers and veterinarians. If point-of-care diagnostic tools became available to allow a producer or veterinarian to diagnose cause of infection in “real-time,” the veterinarian could recommend more specific actions such as: prescribe a specific antimicrobial, recommend no treatment as the prognosis for recovery is good, or administer a biologic or alternative treatment that is targeted to the infection. This will be a particular area of benefit for the livestock sector.

Some species have well-established breeding programs with integrated genomics. Genomic evaluations of dairy cattle began in Canada in 2009^{65,66} and are published by the Canadian Dairy Network (CDN). However, other parts of the livestock sector have not adopted genomics to the same extent. Large multinational companies play an important role in developing livestock genetics, some of which are based in Ontario. Genomics technologies are essential to accelerate advances in breeding programs. Several of the minor species do not have comprehensive historical phenotypic records to support the development of genetic markers and the adoption of genomics. If phenotyping systems and record-keeping can be developed, new genomics technologies could allow these sectors to leapfrog over older processes and adopt high-efficiency breeding programs fueled by world-class innovation.

Genomics R&D will contribute to a better understanding of the biology of an animal and how its performance is impacted by—and can be improved in—different environments by collecting a great deal of precise data and ensuring the bioinformatics capacity to properly interpret the data.⁶⁷ This is particularly relevant to beef cattle that spend most of their lives outside of enclosed environments.^{68,69} Commercial crossbred genomic data could be used to inform selection decisions in pedigreed populations.



4.3 Microorganisms and Microbiomes

Microbial communities are an essential component of every ecosystem. Humankind depends on these microbial systems for primary production, ecosystem services, and industrial processes including food processing. Single-cell microbial genomics is a growing field with a significant role to play in both extending and pulling together understanding of microbial communities in the environment, and can be applied in different ways, from establishing gene linkages to *de novo* reconstruction of new genomes, to whole-genome population studies.⁷⁰



Genomics is providing better tools for understanding the soil microbiome (that consists of complex microbe-plant and microbe-microbe interactions, as well as interactions with the microfauna). This is a rich domain for current and future research aimed at improved agronomic performance of both individual crop species and different species in rotation, including the possibility of breeding cultivars in rotations (e.g., a cereal and a legume) so that there are improved synergistic and complementary benefits for the overall performance of the agroecosystem.

In agriculture and food, microbes are involved in many aspects of plant and animal health and are also used extensively by the food and beverage industries. Most plants have endosymbiotic associations, including arbuscular mycorrhizal fungi and other endophytes, and legumes use rhizobia to assist with nitrogen fixation. Rhizospheres consist of complex soil-plant microbiomes. The rumen microbiota are essential for the digestion of forage by cattle and sheep, as well as other ruminants.



There is growing recognition that diet affects the composition and metabolic activity of the human gut microbiota, which in turn can impact health. Molecular technologies have greatly advanced understanding of the complexity and diversity of the gut microbial communities and diet, particularly macronutrients, which have a major role in shaping the composition and activity of these complex populations.^{71,72} This is an area where AAF genomics research could be linked with human microbiome and metabolism research to determine approaches to optimize diets for both individuals and populations.



There are many fermented food and beverage products.⁷³ These include both animal products (e.g., yogurt, cheese, etc.) and plant products (e.g., yeast-leavened bread, pickles, sauerkraut, beer, wine, etc.), and there is interest in understanding and genetically altering the associated microorganisms to improve processing systems or to provide health benefits to consumers (e.g., prebiotics, probiotics).⁷⁴

The Canadian dairy food industry has applied genomics to cheese making and ripening, including studies of microbial activity (e.g., in local milks and cheeses) and real-time quality control.⁷⁵ UofG researcher, Dr. Gisele LaPointe is working on increasing Parmalat Canada's cheddar manufacturing capacity by implementing metagenomic, metaproteomic, and metabolomics tools adapted to meet the technical requirements of cheese production with the goal of increasing production to meet market demand while utilizing Canadian milk.



4.4 Bioproducts and Bioprocesses

Further development of Ontario's bioeconomy is an important strategic direction for the province for economic growth and mitigation of greenhouse gas emissions.⁷⁶ Ontario has long been Canada's manufacturing heartland, with strengths across the value chain starting with natural resources (oil refining and minerals), chemicals and plastics manufacturing (\$21.8B and \$16.3B, respectively)⁷⁷, as well as high-value products manufactured using these materials, notably for the auto parts and auto manufacturing sector (\$100B)⁷⁸. Global trends and consumer preferences are moving manufacturing towards a focus on sustainability. Biotechnology is playing an essential role in driving this shift globally, allowing materials to be manufactured from renewable resources like biomass instead of oil. The Organization for Economic Co-operation and Development (OECD) estimates that industrial biotechnologies will contribute \$390B in Gross Value Added to OECD nations.⁷⁹ With its abundant biomass resource, reliable transportation infrastructure (via trucking, rail, and deep-water ports to the United States) to easily move products, and a burgeoning hybrid biochemical cluster in Sarnia⁸⁰ and downstream manufacturers like those in the auto sector that are eager to incorporate renewable materials, Ontario is well positioned to expand substantially this sector of its economy.

Genomics is playing a key role in moving from petroleum-based feedstock to renewable biomass feedstock. Ontario's agriculture sector has already been producing feedstock for industrial purposes including corn and soybean. It is estimated that 37% of Ontario-based corn is being used as a feedstock for biofuel production and other industrial processes, making bio-based feedstock a major source of revenue for Ontario growers (Suncor's 400M LPY ethanol plant in Sarnia consumes 20% of Ontario corn alone).⁸¹ Genomics has helped drive this by



developing breeds of corn specifically for industrial use, notably by boosting yields, helping to drive economical use. Canada's Industrial Bioproducts Industry identified positioning Canada as a global leader in feedstock development as a top priority, with genomics pointed to as a key enabling technology.⁸² Genomics is helping drive second generation or advanced biofuels that use sugars obtained from inedible cellulosic biomass. Ontario-based Comet Biorefining has demonstrated the success of their technology in enzymatically converting waste corn stover into sugars to be used as feedstock for fermentation processes, and a cooperative has been established to source corn stover from producers. An offtake agreement with BioAmber, an industrial biotechnology company with manufacturing facilities in Sarnia, Ontario, is also in place to use these sugars

for production of biochemicals. This has the potential benefit of greater GHG reductions compared to corn-based sugars, provides growers with a new revenue source for a current waste product, and circumvents the "food vs fuel" debate. Further diversification of bio-based feedstocks extends to methane, which can be derived from the anaerobic digestion of food waste by microorganisms and can be used both directly as an energy source for heating (as renewable natural gas) as well as a source for fermentation into a range of chemical products. There is significant opportunity for genomics to optimize the production process, both by improving output of methane by optimizing the microbiome in anaerobic digesters as well as in developing monitoring tools for more stable production.



Fermentation processes have long been used to produce biochemicals but were limited in the range of possibilities. Recent advances in genomics have allowed for the engineering of microorganism metabolism to produce a wide variety of biochemicals from sugars that can directly replace their petroleum-derived equivalent. BioAmber is successfully manufacturing succinic acid (used in producing polymers, resins, and solvents) from sugar streams, which materially decreases the carbon footprint. These same principles could be used to develop a process for the manufacture of adipic acid, used in producing nylon.

A genomics-driven bioengineering approach has been developed by the University of Toronto's team at BioZone led by Dr. Radhakrishnan Mahadevan to convert sugars into value-added industrial chemicals such as adipic acid. Adipic acid alone has a market of 2.2 million tonnes; chemicals that can be derived from it have similarly large markets. BioAmber is positioned to apply the results from this research program to the development of next-generation chemicals.

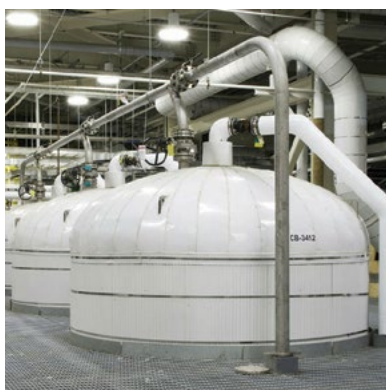


Photo: BioAmber Sarnia Inc.

Specialized yeasts are also being developed that can metabolize a wider range of sugars, including pentoses that are derived from lignocellulosic materials like corn stover, increasing the yield of fuel or chemicals from biomass. Microorganisms that metabolize methane, known as methanotrophs, are also being engineered to be able to convert methane feedstock into a range of useful products including bioplastics. Dr. Trevor Charles at the University of Waterloo, and colleagues, have been working towards this goal, applying synthetic biology tools to engineer these microbes to manufacture polyhydroxyalkanoates (PHAs), plastics that are both renewable and biodegradable.



5. Ontario's Genomics R&D Capacity and Organization

AAF genomics research and development (R&D) involves both public and private (including for-profit and not-for-profit) sector organizations working both intramurally and collaboratively, provincially, domestically, and internationally.

Ontario has established stellar research capacity in academia, in government (provincial and federal) facilities, and in the private sector; engaged in AAF sector R&D, as well as allied biosciences R&D. Ontario has more than 20 universities across the province⁸³ and 26 colleges providing education and training in agriculture, animal, food, and related practices.⁸⁴ Collectively, these academic, public and private sector organizations perform basic and applied research, fund R&D projects, provide education and training to develop scientists, technicians, and other highly qualified personnel (HQP), provide scientific infrastructure, and engage in technology transfer and commercialization.

AAF R&D in Ontario benefits from a long-standing partnership between the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) and the University of Guelph. OMAFRA and UofG signed a ten-year agreement in 2008 that supported research funding and infrastructure, laboratory and veterinary capacity programs, a knowledge translation and transfer (KTT) program, and an HQP scholarship program.⁸⁵ Between 2008 and 2013, UofG received \$350 million for its agri-food and rural research programs, laboratory services, and veterinary clinical education program. The OMAFRA-UofG Agreement has been supporting genomics research projects. In February 2018, the OMAFRA-UofG Agreement was renewed for the next 10 years with a provincial government investment of \$713 million to further discovery and innovation, and position Canada as a world leader in agri-food.⁸⁶

The Agricultural Research Institute of Ontario (ARIO) is a corporate body that reports directly to OMAFRA to provide strategic advice and to advocate for agricultural research in the province.⁸⁷ ARIO owns 15 research stations across the province, which are operated and managed by UofG. Other AAF research centres in the province include the Cool Climate Oenology and Viticulture Institute (CCOVI) at Brock University,⁸⁸ and AAFC federal agriculture and food research centres in Harrow, London, Guelph, and Ottawa, which are part of a more extensive network of research centres across Canada. In addition, the CFIA has a network of thirteen reference and research laboratories across

Canada, with three of these in Ontario based in Ottawa and the Greater Toronto Area. The Public Health Agency of Canada also has a Laboratory for Foodborne Zoonoses based in Guelph.

Ontario also has a variety of food and beverage innovation centres that have recently been inventoried and reviewed under the auspices of Food and Beverage Ontario (FBO) as one of the Ontario-Canada *Growing Forward 2* initiatives.⁸⁹ The commercialization of agri-food innovation is supported through a variety of organizations, including Livestock Research and Innovation Centre (LRIC) and members of the Agri-Technology Commercialization Centre (ATCC): Oilseed Innovation Partners (OIP), Bioenterprise, and Ontario Agri-Food Technologies (OAFT).

Although most of the AAF R&D funding in Ontario has not been directly allocated to genomics, there have been numerous AAF genomics research projects relevant to Ontario carried out in Ontario or elsewhere in Canada funded by Genome Canada⁹⁰, the Genome Centres, NSERC⁹¹, and the AAFC.⁹² Ontario Centres of Excellence (OCE) have also funded some agricultural bioproducts projects.⁹³ These projects and programs have covered an array of subjects and commodities. For example, in its 2017/2018 report,⁹⁴ Genome Canada refers to recent projects concerned with enhanced beef and dairy cattle genetics, pollinator health, porcine health, wheat, barley and sunflower development, improved grape wine production, production of high-value plant metabolites, and improved *E. coli* detection in food processing systems. NSERC has funded projects on mycorrhizal fungi and the corn endophytic biome, while AAFC has funded projects largely focused on crop protection and crop development of major cereal and oilseed crops, as well as insect genomics and metagenomics-based ecosystem biomonitoring.

Ontario Genomics, in collaboration with Genome Canada and numerous partners, has been an integral contributor to this rich AAF research and innovation ecosystem with grants ranging from \$25K SPARK Program to \$10M Large-Scale Applied Research Programs (LSARP). It has helped develop research and development strengths in Ontario through the funding of a broad range of projects of direct interest to the AAF Sector (Table 1)⁹⁵ and concerned with a cross section of commodities including, but not limited to canola, soybeans, tomatoes, greenhouse vegetables, dairy, swine, turkeys, and bees.

Table 1

Ontario Genomics - Agriculture, Agri-Food and Aquaculture Projects			
Program		Title	Total Project Funding
Genomic Applications Partnership Program (GAPP)	1	Increasing Yield in Canola Using Genomic Solutions	\$3.7M
	2	Translating OMICS for competitive dairy products	\$1.3M
	3	Application of genomic selection in turkeys for health, welfare, efficiency and production traits	\$6M
	4	A genetic toolbox for tomato flavour differentiation	\$1.8M
	5	Genomics for a competitive greenhouse vegetable industry	\$2.4M
	6	Genomics Driven Engineering for Bio-Nylon	\$5.7M
	7	Commercial application of genomics to maximize genetic improvement of farmed Atlantic salmon on the East coast of Canada	\$3.8M
Pre-commercial Business Development Fund (PBDF)	8	New acquired immunity chemicals for soybean crops	\$200k
	9	Reducing boar taint in pigs through the use of genetic markers	\$364k
	10	Transgenic Plants with Enhanced Agronomic Traits	\$20k
	11	DNA probe identification and testing for use on 3D-biochip product	\$310k
SPARK Program	12	CRISPR/Cas9 conjugative plasmids for microbiome control	\$25k
	13	Discovery of the microbiome of corn silks: The entry point for fungal pathogens including Fusarium	\$25k
	14	Developing biosensors to promote healthy plant growth	\$25k
	15	Developing diverse chemical libraries	\$25k
	16	Methane to bioplastics: Bacterial strains for production of high value bioplastics on methane feedstock	\$30k
Large Scale Applied Research Project (LSARP) Competition	17	Increasing feed efficiency and reducing methane emissions through genomics: A new promising goal for the Canadian dairy industry	\$10.3M
	18	Sustaining and securing Canada's honey bees using 'omic tools	\$7.3M
	19	Towards a sustainable fishery for Nunavummiut	\$5.6M
Disruptive Innovations in Genomics (DIG) Competition	20	Development of advanced genetic toolbox for Sinorhizobium meliloti to enable genome scale engineering	\$250k
	21	A cell reporter system for the functional screening of insect odorant	\$234k
Bioinformatics and Computational Biology (B/CB) Competition	22	ePlants pipeline and navigator for accessing and integrating multi-level 'omics data for 15 agronomically important species for hypothesis	\$250k
	23	Applying genomic signal processing methods to accelerate crop breeding	\$220k
	24	Large Data Sets and Novel Tools for Plant Biology for use in International Consolidation-Tier Data Repositories	\$1M
Seed Funding	25	Metabolomics Profiling of Polyphenolics in Ice Syrup Grape Pomace	\$21k
	26	Development of a model system for crop development in monocots using Brachypodium distachyon	\$25k
	27	Microbial community analysis related to plant growth promotion by Spanish River Carbonatite	\$28k
	28	Understanding the Role of Microorganisms in a Highly Productive Corn	25k
	29	Development of Allele-specific Markers to Identify Compatibility of Hazelnut Varieties	\$25k
	30	Canada's Ten Thousand Genome Project	\$25k
	31	Development of Genetic Markers for Genetically-assisted Breeding of Mite-resistant Honey Bees in Ontario	\$26k
Competition II	32	Functional genomics of Arabidopsis	\$1.8M
	33	Functional genomic analysis of soil micro-organisms	\$5.8M
ABC	34	Genomics for Crop Improvement: Agricultural Pest Management (GAP-M)	\$6.4M

Projects include both Genome Canada and Ontario Genomics funding programs



6. Sector Connections

Genomics-based technologies, coupled with precision agriculture methodologies and artificial intelligence, will revolutionize the agriculture and agri-food sector. These opportunities and advances are linked with and will have positive impacts for other priority sectors across Ontario and around the world.

6.1 Links with Agroforestry, Aquaculture and Human Nutrition

There are many areas of genetic and metabolic similarity among the species that comprise the renewable resources sectors, meaning that research on tree or fish genomics could potentially contribute to advances in crop and livestock genetics and vice versa. In the same vein, advances in understanding monogastric gut microbiomes (e.g., pigs) could contribute to a better understanding of the human gut microbiomes. This is currently a potentially rich domain for multidisciplinary genomics R&D that may become more prominent in the future.

Similarities and links among species provide a rich domain for multidisciplinary genomics research with potential opportunities for all of the renewable resource sectors.



Ontario already has a well-established agroforestry sector⁹⁶ that includes sugar maples, Christmas trees, and nut trees that in 2016 generated farm cash receipts exceeding \$46 million.⁹⁷ The Ontario aquaculture industry produces primarily rainbow trout, which accounts for 95% of the Ontario market, but also produces tilapia, Arctic char, brook trout, smallmouth and largemouth bass, and cyprinid baitfish with a farm-gate value of more than \$19 million.⁹⁸

A primary purpose of agriculture is to provide food and feed for nutrition and wellness, and much of crop and livestock research has focused on output traits (nutritional and organoleptic qualities), as well as input traits (yield, performance, resistance to diseases/pests, etc.). Ontario also has nutrition and dietetics programs at several universities in the province⁹⁹ and, along with this, opportunities for multidisciplinary R&D using genomics-based approaches aimed at producing foods and diets with enhanced nutritional and health benefits (e.g., functional foods, nutraceuticals, probiotics, etc.).

Genomics-based approaches could contribute to the management and reduction of antimicrobial resistance (AMR), which is a high-profile issue with implications for both human and animal health.¹⁰⁰



6.2 Links with Big Data and Artificial Intelligence

Technologies such as remote sensing, satellites, robotics and unmanned aerial vehicles (i.e. drones), have driven farming into the digital age.^{101,102} Progressive farmers are now faced with large amounts of data about the environment and crop development.¹⁰³ In this era of digital agriculture, the most notable need common across all segments of the agriculture and agri-food industry is the need for data platforms to collect, compare, annotate, combine, analyze, store, interrogate, and share large data sets that combine different types of information, including genotypes, phenotypes, and environmental conditions.

Phenomics is an emerging field of science concerned with the measurement of physical and biochemical traits belonging to a given organism as these change in response to genetic mutation and environmental influences. In precision agriculture, phenomics can help industry improve both product development and its decision-making tools.¹⁰⁴ Capacity in this area will allow Ontario to respond to trends in precision agriculture, trade, and increased competition in global markets, as well as consumer demand for agri-food sustainability.

Large-scale phenotyping will be combined with massive genotyping efforts and other 'omics data to produce even more useful insights.¹⁰⁴ However, gaps in high-throughput phenotyping capability must be addressed to achieve these outcomes. In crops, for example, while above-canopy phenotyping (drones, satellites) technology is common and ground sensor technology is developing rapidly, phenomics is limited by a lack of fast, inexpensive, and relevant below-canopy measurement.

Full automation of phenotyping platforms is gaining momentum and has the potential to enhance product quality, management practice, well-being, sustainable development, and animal health, ultimately contributing to better human health. Combining the phenotypic data with genomics, transcriptomics, and microbiota from animals, is facilitating a tech-enabled era of precision animal agriculture. Farmers, breeders' associations, and other industry stakeholders can now continuously monitor and collect animal- and farm-level information using less labor-intensive approaches and the data collected can be presented to farmers in a way that they can make quick and evidence-based decisions.¹⁰⁵

Genomics tools coupled with big data and AI will enable rollout of new varieties of crops more quickly to feed our growing population in an ever-changing world.

As the agriculture and agri-food industry is under more public scrutiny, blockchain technology will help boost consumer confidence. Use of blockchain technology in agriculture is on the rise, and it will be invaluable for food safety, traceability, and processing. This technology will allow farmers using sensors and handheld devices to gather data about crops right from seeds, allowing traceability through the entire supply chain right up to consumer purchase.

The opportunities for capacity development in Ontario to address the gaps in data access and handling include:

- **Development and adoption of robotics, automation, and remote sensing capabilities to collect useful quantitative phenotypic data.** Precise, well-managed locations and projects will be key to acquiring reliable data.¹⁰⁴ Similar gaps in phenotyping exist in animal agriculture, horticulture, and aquaculture. Agricultural robots are being developed and programmed to handle essential agricultural tasks, such as harvesting crops at a higher volume and faster pace than human labourers. Examples include robotics to help farmers find more efficient ways to protect their crops from weeds (Blue River Technology); and robotics to help harvest crops (Vineland Research and Innovation Centre). Wearable biosensors in livestock are already helping monitor animal health and improve management practices.¹⁰⁶
- **Leveraging computer vision and deep-learning algorithms to process data captured by drones and/or software-based technology to monitor crop and soil health.** Rapid advances are being made in developing deep learning applications that identify potential defects and nutrient deficiencies in soil. Drones are being used to determine crop yield, identify nutritional deficiencies, or detect the presence of disease in a field (A&L Canada Laboratories Inc.). Trace Genomics (U.S.A.) is developing monitoring systems that use machine learning to provide clients with a soil's strengths and weaknesses.
- **The integration of big data across the entire supply chain, which is especially important in food processing.** It is predicted that genetic detection and verification will be used at multiple points in food processing in the future. Integrating these large data sets across the supply chain will require expertise to store and interrogate these types of data sets. There is an opportunity for machine learning and artificial intelligence to assist in data collection, analysis, and interpretation for product development. Globally, companies are developing these tools to improve product development in animal and plant breeding, such as NRGene (Israel) and Benson Hill Biosystems (U.S.A.). To maximize the value of the massive amounts of data being collected along the value chain, new ways of integrating big data will be needed to analyze genomics information across agricultural processes.

- **The development of machine learning models to track and predict various environmental impacts on crop yield such as weather changes through predictive analytics.** Ontario has a wealth of livestock and crop genomics data. Machine learning models should be developed with these data to help predict the best breeding stock for farmers.

Leveraging emerging AI-driven technologies and big data will help improve efficiencies, address sector challenges, and help increase livestock and crop yields in a sustainable manner for a growing and ever-changing planet.



6.3 Links Between Ontario's Agriculture and Agri-Food Sector and the World

In 2015, the member states of the United Nations adopted the 2030 Agenda for Sustainable Development, which has 17 Sustainable Development Goals.¹⁰⁷ The Government of Canada is committed to supporting the implementation of these goals. The goals most aligned with the AAF sector globally are: to end hunger, achieve food security and improved nutrition, promote sustainable agriculture, ensure healthy lives, promote well-being for people of all ages, take urgent action to combat climate change and its impacts, and sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss. Ontario, as the most populous province with the largest share of the national GDP, can play a key role in this international development initiative.

The earth's population is expected to increase from the current population of 7.6 billion to 8.6 billion in 2030, 9.8 billion in 2050, and 11.2 billion in 2100.¹⁰⁸ To accommodate the increased demand for food, world agricultural production needs to rise by 50% by 2030.¹⁰⁹ In general terms, increased food production must largely take place on the same land area while using less water and coping with climate change impacts. Advances in crop genomics will be one of the best approaches available to increasing output per unit area and reducing input requirements while also dealing with adverse environmental conditions resulting from changes in global weather patterns and climate.¹¹⁰

With its well-developed AAF sector, Ontario can play a key role in providing food exports, food aid, and technology transfer by educating and training highly qualified personnel (HQP), including HQP with genomics expertise, and providing other forms of international development assistance.



7. Environment and Climate Change

There is an overwhelming scientific consensus that anthropogenic climate change is a reality.¹¹¹ This, along with associated variability in year-to-year weather patterns, will have a major impact on agricultural production. The AAF sector is currently focussed on adaptation to and mitigation of the impacts of climate change.

7.1 Adaptation

As a result of climate change, it is expected that most regions of Canada will warm during the next several decades and a changing climate, especially at higher latitudes, can exert both positive and negative impacts on agricultural production.^{112,113} Although future impacts cannot be predicted with certainty, many factors will need to be studied further as mean temperatures and greenhouse gas levels increase. For crops, these include temperature increases; extreme weather events (e.g., drought, flooding); water availability, especially during critical events (germination, pollination, seed set, etc.); changes in the incidence and severity of weeds, pests, and diseases; and the effect of elevated levels of CO₂ on crop growth and crop quality (e.g., the possibility of higher yields but lower nutrient and protein levels). For livestock, there could be impacts associated with increased stress due to heat and humidity, reduced feed quality, and increased susceptibility to diseases.

In certain regions, however, there may be expansion of the growing season and milder and shorter winters that might increase crop productivity and permit expanded crop diversity. For example, the Great Clay Belt of Northeastern Ontario has about 1.7 million hectares of land that could be cultivated, and very little of this land has currently been developed for production.^{114,115} There could also be benefits for livestock production due to lower feed requirements, increased survival rates of the young, and lower energy costs. In addition, soil quality might be improved because of enhanced carbon sequestration, which contributes to mitigation and reduced greenhouse gas emissions as a result of changes in land use.

Advances in genomics are providing the basis for sustainable intensification of agriculture and heightened resilience of crops to climate change. The availability of high-quality reference genomes has been growing due to

the widespread application of genome sequencing technology, and advances in population-level genotyping have contributed to a more comprehensive understanding of genomic variation. These data facilitate the move towards plant pangenomics, providing deeper insights into the diversity available for crop improvement, breeding of new cultivars, and adaptation to different agronomic systems for both field crops and greenhouse crops, and other kinds of controlled-environment agriculture (e.g., vertical farming).¹¹⁶

For livestock, adaptation to climate change will require a multifaceted approach including housing, reproduction, nutrition, and health care, but genomics will play a role in the genetic measures taken for adaptation of livestock to climate change.¹¹⁷

Biological invasions by non-native species, including new diseases, are expected to increase as the effects of climate change on biological communities manifests itself. Metabarcoding and metagenomic approaches provide a means of monitoring for the appearance of invasives. Genomic markers enable accurate tracking of invasive species' geographic origin, and new genomic tools are promoting insights into questions about invading organisms under climate change, such as the role of genetic variation, local adaptation, and climate pre-adaptation. These tools can provide more effective means to identify potential threats, improve surveillance, and assess impacts.¹¹⁸

7.2 Mitigation

Mitigation, in relation to the AAF sector, involves reducing greenhouse gas (GHG) emissions associated with agricultural and food production, processing, transportation systems, and increasing carbon capture. The major emissions associated with the AAF sector are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). On-farm CO₂ comes from burning fossil fuels to run farm machinery, decomposition of organic matter from intensive tillage operations, and crop residue burning. The CH₄ is the result of ruminant digestive processes and anaerobic decomposition of organic matter. The N₂O comes from nitrification in soil, denitrification in soil, and in manure storage. On the other side of the ledger, agricultural production removes carbon from the atmosphere through photosynthesis and potentially through carbon sequestration in soil.¹¹⁹ Dr. Peter Pauls, Dr. Michael Emes, and Dr. Ian Tetlow at the University of Guelph and their collaborators at Benson Hill Biosystems (BHB) have identified genes related to seed yield in different plants that can be incorporated into canola. The new genes are expected to significantly enhance crop sustainability and productivity by increasing photosynthetic capacity and carbon capture without negatively impacting seed quality. The university's researchers are combining their strengths with scientists at Benson Hill Biosystems, an innovative crop improvement company, to produce game-changing varieties of canola for producers across Canada.

Apart from the net impact on the carbon cycle of photosynthesis, respiration by crops and livestock, and fossil-fuel combustion, on-farm GHG emissions result primarily from microbial activity (e.g., in the rumen, soil, and manure). Altering the microbiota, along with other agronomic and husbandry practices, could reduce these emissions and genomics approaches and can contribute to the development of more beneficial microbiomes.



8. Biodiversity Genomics

Agricultural biodiversity includes the components of biological diversity of relevance to food and agriculture, and to the biological diversity that constitutes agroecosystems. It includes the genetic resources for AAF—plants, animals, microbes, fungi—and the components of biodiversity that support the ecosystem services for agriculture.¹²⁰

Biodiversity is the basis of resilient agriculture. It includes all species of crops and domesticated livestock and the variety within them, as well as all of the ecosystem services, such as soil and water conservation, maintenance of soil fertility and biota, and pollination, all of which are essential to sustain agriculture and human well-being. In addition to sustaining livelihoods, biodiversity is essential for: ensuring the production of food, fibre, fuel, and fodder; maintaining other ecosystem services; and allowing adaptation to changing conditions, including climate change.

Biodiversity genomics is a relatively new field that can be defined as the use of DNA as part of a larger framework of integrated data to answer questions about the diversity and processes that govern the patterns of life on the planet and how they change.¹²¹ Ontario is a world leader in this field due to the work carried out at UofG's Centre for Biodiversity Genomics (CBG) where the global DNA barcoding initiative was started.¹²²

DNA barcodes use a small fragment of an organism's DNA to identify the species to which the organism belongs. They are powerful tools, which can be used to help catalogue biodiversity and advance understanding of the distribution and interactions among species. This technology is applied to develop solutions ranging from breeding better plants, protecting and improving human and animal health, and detecting marketplace food fraud, to enabling detection of invasive pests.



9. Genomics in Society

Because its applications can directly affect the environment and human health and nutrition, AAF genomics R&D cannot flourish without being addressed in the context of ethical and policy questions to determine whether there is the social license to apply them in practice. Policies need to be socially acceptable in order to be sustainable and effective. This does not mean that they should be constructed to appease the public at large, but it does mean that policies should be informed by the views of a public that is accurately informed. Therefore, there is a need to educate and engage the public at large about advances in genomics, including the ethical, legal and social implications that they pose. Policy making must incorporate an ongoing analysis of public perception of genomics to ensure that it constructively addresses areas of public concern and the apprehensions of society towards genomics-based applications.

Genome Canada and the Genome Centres have therefore created significant expertise in Canada through the funding of integrated GE³LS studies—the Ethical, Environmental, Economic, Legal, and Social aspects of genomics. GE³LS studies investigate questions at the intersection of genomics and society. They provide stakeholders the insights needed to anticipate impacts of scientific advances in genomics, avoid pitfalls, and cultivate success.¹²³

9.1 Regulation

A key component of social legitimacy relates to public confidence and trust in its regulatory institutions.

The *Constitution Act, 1867*, stipulates that the provinces and the federal government have shared jurisdiction for agriculture.¹²⁴ Consequently, both Ontario and Canada have responsibilities for legislation and regulations pertaining to the AAF sector^{125,126} and the two levels of government must work together to meet the needs of the sector. In July 2017, Canada's federal, provincial, and territorial (FPT) ministers of agriculture endorsed the *Plant and Animal Health Strategy for Canada*¹²⁷. The strategy is a shared vision between partners across governments, industry, academia, and others, and charts a path forward for collectively addressing evolving risks to plant and animal health.



The CFIA proactively engages with international partners to develop international science-based standards and to promote the Canadian science-based regulatory system. The agency also negotiates with foreign trading partners to resolve scientific and technical issues related to food safety and animal and plant health, and thereby contribute to market access for Canadian AAF sector products.¹²⁸

Regulatory approval is an important milestone on the road to achieving the social license to introduce novel agricultural products. These products—including plants, feeds, veterinary biologics, and fertilizer supplements—are regulated by the federal government, with the CFIA being the lead agency. Health Canada is the regulatory authority for foods, veterinary drugs, and pest control products.¹²⁹ Novel agricultural products in Canada are regulated using existing legislation and a key aspect of the Canadian regulatory system is the application of a products-based approach, which means that regulators evaluate the end products of innovation, rather than the process by which they were developed.¹³⁰ This combination of using existing legislation for the agricultural products of biotechnology and focussing on the characteristics of the product, rather than the means through which the product was developed, is consistent with an evidence-based approach and is arguably fairer and more efficient than other approaches. In the international arena there appears to be a trend towards regulatory systems more widely adopting the Canadian model.^{131,132,133}

Genomics science at the CFIA aims to develop and apply new knowledge and expertise, and faster, more accurate, and cost-effective diagnostic technologies, tools and methods for detection, isolation, identification, and characterization of new and emerging pathogens, pests, and invasive species relevant for its three business lines (plant, animal, and food). The application of genomics technologies is already making a difference at the CFIA by providing knowledge to support more efficient and effective decision-making practices.

Genomics-based approaches have a key role to play in the development of improved, rapid, and inexpensive diagnostic tools available to detect zoonotic diseases and other infectious diseases, to enhance food safety, and to assist with preventing or resolving trade disputes (e.g., rapid diagnostic tests to distinguish between inoculated animals and infected ones).

9.2 Intellectual Property

Historically, proprietary rights for agricultural innovations were considered non-existent, or inaccessible, since germplasm was presumed to be a communal resource to be shared freely. It wasn't until the 1960s, with the implementation of the International Convention for the Protection of New Varieties of Plants, that proprietary protection started to become available.



Issues related to intellectual property (IP) for agricultural innovations are complex. For example, there are situations where protective mechanisms meant to foster agricultural innovation conflict with germplasm sharing practices – and these differ from jurisdiction to jurisdiction. This makes it exceptionally challenging to navigate and work within the various domestic and international regimes to advance genomics innovations in agriculture.

The Canadian Intellectual Property Office (CIPO) is a federal agency responsible for the administration and processing of the greater part of IP in Canada. CIPO's mandate is to deliver IP services and to increase awareness, knowledge, and effective use of IP by Canadians. A Canadian perspective on IP issues in relation to agricultural genomics has been addressed recently in some detail,¹³⁴ including the challenges related to translating agricultural innovation arising from genomics research into products for end users, the inability in some cases to access inputs that are necessary for development but are protected by IP rights, and the arguments for and against the application of IP to genetics and living materials.

Ontario Genomics, Genome Canada, and the other Genome Centres across Canada can play a key role in supporting research focused on resolving issues related to how regulatory and IP systems affect incentives for the development of products derived from agricultural genomics R&D.

9.3 Communications and Engagement

Advances in genomics need to be accompanied by a communications approach that addresses actual benefits, while balancing potentially unknown risks associated with these advances. This communication will need to understand what the varying interests and concerns are of a variety of stakeholders with varying degrees of knowledge of genomics and agriculture. These stakeholders include researchers (public and private sector); sector stakeholders (growers, input suppliers, shippers, wholesalers, retailers, etc.); decision-makers (research managers, funding agencies, etc.); and citizens and consumers of agri-food products.

There is a need to have communicators who are broadly accepted as being knowledgeable and impartial. There needs to be a high level of openness and transparency about the risks and the benefits posed by the application of scientific advances, and there needs to be a direct link to customers and consumers.

This latter criterion can be particularly challenging in today's world of fragmented and numerous information sources. In general, people prefer to be informed through media that they use routinely and with which they are comfortable. This now includes various social media platforms; radio or television broadcasts; print media such as books, magazines, and newspapers; meetings and presentations; etc. Consequently, connecting with target audiences is an increasingly difficult challenge. Indeed the "science of science communication" has become a



social sciences subdiscipline that is attracting increasing attention.^{135,136} This challenge is not unique to genomics or biological research but applies across the natural sciences where scientific and technological advances are part of the everyday life of many people and can be difficult to explain to a lay person. Success in communication would result in a more informed electorate in an era where so much policy relates to technological advances, to increased interest in science, technology, engineering, and mathematics (STEM) careers, and increased support for science and technology.

In an era where so much policy relates to technological advances and the increased need and support for genomics-based applications, success in communications is essential to ensure a more informed public.

Consultations in Ontario and across Canada in 2017 concerning the development of AAF genomics strategies inevitably led to discussions about engagement with various audiences in the context of achieving a wider understanding of the reasons for undertaking genomics research and what expected benefits would result from implementing the innovations resulting from this R&D. Suggestions to address this issue include educating both students and educators about new advances and their benefits and risks as an important first step in gaining social acceptance, improving consumer and other end user adoption rates of innovations by better communicating information, and enhancing efforts to gain social acceptance of innovations by communicating trade-offs early and promoting success stories on social and other media. This suggests that a communications plan should be proactively addressed as an integral component of new projects, programs, and initiatives.

These ideas that have come forward represent some first steps that could provide the basis for a comprehensive communications and engagement strategy that would contribute to informed acceptance of technological advancements taking advantage of genomics innovations. It is an area also where Genome Canada, Ontario Genomics, and the other regional Genomics Centres could play a leadership role through GE³LS support for “science of science communication” initiatives.

9.4 Big Data Management and Data Sharing

Big data refers to data sets with such large volume or complexity that they are difficult to process using traditional data processing applications. Big data infrastructure is a framework, which is used for storing, processing, and analyzing big data.¹³⁷ Big data analytics covers collection, manipulation, and analyses of massive, diverse data sets that contain a variety of data types including genomic data along with phenotypic and environmental data to reveal hidden patterns, cryptic correlations, and other intuitions on a big data infrastructure. Big data management is a



major challenge for the future, and the availability of adequate human and machine capacity to carry out this work in a timely and efficient way needs to be addressed along with approaches to avoid duplication.

Big data management will be particularly important in advancing the emerging field of environmental DNA (eDNA)—genetic material obtained directly from environmental samples without any obvious signs of biological source material.¹³⁸

Further, it will play an important role in the emerging fields of integrating genomics with precision agriculture—to develop crops with combinations of genes that lead to the best performance in specific environments¹³⁹—and phenomics—the measurement of change in response to genetic mutation and environmental influences^{140,141}—as well as many other areas.

Another issue that was raised during recent genomics strategy meetings, and that has an international development dimension as well as a domestic dimension in terms of global equity, is data sharing and the concept of open access to scientific data.¹⁴² Currently genomics datasets are being published under an array of different access regimes, with inadequate agreement on appropriate protocols and standards to effectively govern access to the massive amount of data being generated. There is a need to ensure that stored data and germplasm can actually be used to improve crops and livestock, and also to ensure optimal benefits to developing nations while simultaneously securing much-needed revenue from newly developed technologies. This is an area that needs to be addressed through national and international forums.



10. Future Actions

10.1 Considerations

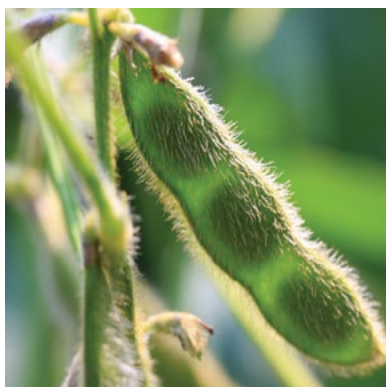
Sequencing costs have declined rapidly in recent years.¹⁴³ In addition, a large number of scientific advances are becoming available that provide powerful tools to understand metabolism and alter it through changes in gene expression and regulation. Together with ongoing advances in informatics that make it increasingly practical to extract useful information from massive datasets, we are entering what some call the Fourth Industrial Revolution where the speed of current breakthroughs is unprecedented and emerging technologies are being rapidly developed in numerous fields, including biotechnology, robotics, artificial intelligence, nanotechnology, and quantum computing.¹⁴⁴

Capacity to innovate in the 'omics field is becoming more widely distributed.¹⁴⁵ Rapid advances using existing knowledge, along with new discoveries that cannot be anticipated at this time, will undoubtedly take place. Ontario, with its abundant human and natural resources, its diversified economy, and its stable institutions and political systems, has the current capacity and potential to participate and even lead in some areas concerned with advances in 'omics research and their application to the AAF sector.

10.1.1 Stakeholder Feedback

Synthesis Agri-Food Network, under the direction of Ontario Genomics, conducted one-on-one interviews with regional and global experts to obtain their perspectives on genomics priorities for Ontario's AAF sector. This was followed by a group stakeholder event held September 25th, 2017, with participants from industry, academia, associations, not-for-profits, and the provincial and federal governments. A summary of the stakeholder feedback is presented in Appendix 3.

Based on the interviews, four areas of opportunity were identified and discussed at the regional stakeholder event: bioinformatics "multi-omics" data integration, climate change adaptation and mitigation, quality traits, and food processing.



Based on the feedback from the stakeholder event, five additional opportunity areas were identified: systems biology, phenomics, rapid diagnostics, microbiomes (all types), and artificial intelligence and machine learning.

Barriers to innovation or application of technologies developed to advance the AAF sector included: public and government acceptance, data management and sharing, the costs and time associated with obtaining regulatory approvals, technology transfer, availability of funding for R&D, the availability and access to research infrastructure, the development and availability of bioinformatics expertise, funding for multidisciplinary teams, and the costs of adoption of genomics technologies by some producers or commodity/industry groups. Many

of these opportunities and barriers are interrelated, and must be considered in conjunction with one another to optimize potential impacts for Ontario's agriculture and agri-food sector.

10.1.2 Assessment Framework

To determine priorities going forward, an approach will be taken that focuses on desired outcomes in areas where AAF genomics innovations can make substantial contributions to achieving major outcomes for the sector in the context of a sustainable AAF system (Figure. 2).

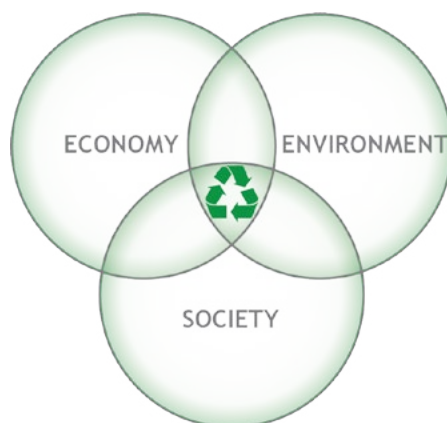


Figure 2 – The goals of a sustainable AAF system are to produce food, feed, and industrial bioproducts using farming and processing techniques that contribute to economic development, protect the environment, and promote human health, wellness and animal welfare.



This could include **translating and applying new products or processes** to result in **consumer benefits** (e.g., food products with enhanced nutritional and organoleptic qualities); **environmental sustainability** (e.g., resilience to biotic and abiotic stressors; reduced requirement for land, water, and other inputs; protecting biodiversity; climate change adaptation and mitigation); **improved profitability** (e.g., for primary producers, processors and others along the value chain); **regulatory support and diagnostics** (e.g., to assist trade, to improve traceability, to monitor food safety, to alleviate the incidence and severity of diseases); and other significant economic, environmental, and social outcomes.

In terms of evaluating and making investments in programs, projects and other initiatives this approach doesn't pick winners (e.g., commodities, technologies, etc.) *a priori*, but considers the cost of a proposed piece of work relative to the social, environmental, and economic benefits that can be reasonably expected for Ontario, both in the short-term and the long-term, and in the context of Ontario's domestic and international roles.



10.2 Recommendations

Continued investment in Ontario's AAF genomics R&D and innovation, as an important component of its overall AAF R&D effort, will contribute to the continued success of the Ontario AAF sector. Agricultural economics research has shown that the rate of return from investment in agricultural research has historically been high and generally remained high, suggesting underinvestment in AAF R&D.^{146,147,148} Increased investment in AAF genomics R&D, coupled with an ongoing commitment to technology development, application, and commercialization¹⁴⁹, in addition to communications, could play an increasingly important part in wealth and job creation in Ontario. This effort could capitalize on Ontario's diversity in AAF products, on its innovation and manufacturing capacity, and on its varied, well-educated, and multitalented workforce.

To build on the strengths and opportunities identified in this report, the following constitute rich domains for Ontario to make advances in genomics research to advance the AAF sector:

1. Augment multidisciplinary R&D using a systems biology approach, with a focus on increased understanding of microbiomes and their interconnectivity to human health.



Biological systems are extremely complex from the molecular, cellular, organismal, through to the ecosystem levels. Applied genomics and systems biology approaches can be used to construct models of complex biological systems. This allows the integration of knowledge from diverse biological components and data into models of the system as a whole. It involves science and engineering that links computational analysis techniques with systematic biological experimentation. This approach involves multidisciplinary research typically including genetics, biochemistry, and molecular and cell biology, along with quantitative modeling that could include probability, statistics, information theory, numerical optimization, artificial intelligence and machine learning, graph and network theory, and nonlinear dynamics.

Ontario has strong capacity in the requisite disciplines at academic institutions and research facilities which are within relatively close proximity to one another. This could create the opportunity to study a variety of microbiomes that are of crucial importance to AAF systems. This includes soil, rhizosphere, rumen, monogastric gut, human gut, and fermented foods microbiomes.

The human microbiome impacts health and disease, and it is likely that much of this impact is mediated through diet, with growing evidence suggesting that gut microbes influence what the human hosts can extract from their diets,

both nutritionally and energetically.⁷⁰ Linking AAF genomics initiatives concerned with the chemical, microbiological, and organoleptic attributes of food with R&D on diets and human nutrigenomics initiatives could have profound impacts for both agriculture and nutritional medicine. There is strong potential to devise not only improved dietary recommendations at the population level, but eventually to develop diets tailored to an individual's microbiota or alteration of diets to improve one's microbiota. This will result in enhanced disease prevention, increased longevity, and improved quality of life.

2. Prioritize programs for sustainable agriculture and food that consider the economy, the environment, and society, for crop production and livestock.



Scientifically based genetics research has for more than a century resulted in major advances in developing crop cultivars and livestock breeds with enhanced performance, resilience, disease resistance, and marketability—both for domestic and export markets.

Apart from considerations related to price, nutrition, and wholesomeness, organoleptic qualities of food (i.e., sensory attributes relating taste, colour, odour, feel, etc.) play a major role in influencing consumer choices. Ontario Genomics, through Genome Canada funded projects, is currently supporting research with Vineland Research and Innovation Centre and Dr. Charles Goulet, Université Laval, focused on breeding new tomato varieties with consumer-focused attributes such as flavour. Because aroma is defined by more than 30 volatile chemicals and dozens of genes, genomics can greatly accelerate breeding with much greater precision than ever before.¹⁵⁰ Genomics R&D can be used effectively to help incorporate traits into food products that could have more appeal to consumers than currently available choices and also provide new products for niche markets—all of which will help to increase economic growth and reduce Ontario's trade deficit.

Environmental benefits accrue from increasing crop output per unit area while making more efficient use of inputs. In some cases, this will enable some land to be returned closer to its native state and increase habitat for native flora and fauna, thus helping to preserve and enhance biodiversity. This is also compatible with efforts to reduce off-farm impacts (e.g., Ontario's target of a 40 percent reduction of phosphorus levels in Lake Erie¹⁵¹) and with efforts to reduce on-farm greenhouse gas emissions, and to increase carbon sequestration.^{152,153}

Genomics research will continue to play an important role in endeavours to increase productivity and profitability, reduce adverse environmental impacts, preserve biodiversity, and contribute to animal health and welfare.

3. Enhance advanced manufacturing and processing systems for both food and industrial bioproducts, including fermentation and traceability.

Crops and livestock can be bred for traits that make them more attractive for different processing systems. Genomics can play a key role in breeding in terms of both food processing and the processing of nonfood products such as industrial bioproducts. Genomics-based approaches can also contribute to safety, optimization, fermentation, and quality control and assurance for processing systems for food and industrial bioproducts.



a. Food processing

Crop diversification is expected to expand in Ontario both in terms of field crops and crops grown in protected environments to take advantage of market opportunities for new food products. Diversification can consist of the same species (e.g., soybeans, corn, dry field beans) being developed for different food uses and the introduction of new species. Genomics advances will help to adapt new species and cultivars to local conditions, will enable the incorporation of traits that will make them better suited to novel processing systems, and will provide tools for traceability to help ensure that crop segregation is maintained when similar crops are developed for different uses. Genomics will also allow better understanding and optimization of the many plant and animal fermented

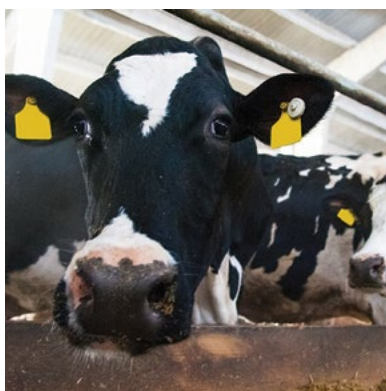
food and beverage products (Subsection 4.3). Diversification of animal products can also be expected to appeal to specialty markets for a diverse society. This diversification of crop and livestock products will help to further strengthen Ontario's already well-developed food and beverage manufacturing sector (see Appendix 2).

b. Industrial bioproducts

As discussed in Subsection 4.4, genomics can be used to develop crops with attributes tailored for use in bioindustrial processes (e.g., soybeans, corn, flax, and other crops are quite versatile in terms of potential food and industrial uses); therefore, building on its current bioindustrial infrastructure, Ontario has opportunities to use genomics technologies to develop crops customized for Ontario-based processing and manufacturing facilities producing bioenergy, biomaterials, and biochemicals.

Since, in some cases, it will be necessary to segregate, and trace crops intended for bioindustrial, biopharmaceutical, and other nonfood uses, genomics can also help to develop tools to enable robust systems for segregation and traceability.

4. Develop rapid diagnostic methods to support regulation and trade, rapid disease detection and traceability in crops and livestock, and biologics to reduce the use of antimicrobials.



a. Rapid diagnostic methods to support regulation and trade, rapid disease detection in plants and livestock, and traceability.

The development of improved diagnostic methods is an area that lends itself to the achievement of short-term (three to five years) important advances as genomics research and innovation contribute to producing accurate, rapid, and cost-efficient diagnostic tests for important crop and livestock diseases. This will assist with disease prevention and quarantine, assist traceability, and provide molecular tools to verify the nature and quality of domestic and exported products. Ontario could focus on supporting work on the precision and robustness of testing, decision-making, and regulatory approaches as it relates to commodities and products relevant to Ontario's AAF sector.

b. Biologics for crops and livestock relevant to Ontario's AAF sector.

Agricultural biologics include substances and compounds that are instrumental in substituting or complementing conventional fertilizers, plant growth regulators and pesticide chemicals used widely in agriculture. These agricultural biologics are significant environmentally as they help in reducing the negative environmental impact of agriculture. They include naturally-occurring solutions, for example, plant extracts, beneficial insects, other organic materials,

and microbial that enable agriculturalists to improve the crop yield and crop quality and promote sustainable development by using naturally derived substances for agriculture.¹⁵⁴

In Canada, veterinary biologics are regulated by the Canadian Food Inspection Agency (CFIA). Veterinary biologics are animal health products such as vaccines, antibody products, and in vitro diagnostic test kits that are used for the prevention, treatment, or diagnosis of infectious diseases in animals, including domestic livestock, poultry, pets, wildlife, and fish.¹⁵⁵

With increasing pressure on agriculture to reduce the use of antimicrobials, viable alternatives are needed. While achievements in this area will likely take place over a longer timeframe (five to ten years) it is an important field for investment. Current alternatives do not have the same efficacy as traditional antimicrobials and have a fairly long development time. Genomics research will enable the development of new and more effective tools for disease detection in crops and livestock, and for vaccines, antibody products, in vitro diagnostic test kits, and novel gene therapies. For livestock, these will help to increase knowledge of animal biology, microbiomes, and the immune system, which will lead to increased disease resilience, better disease management, more effective vaccines, and the responsible use of antibiotics, all of which is highly relevant due to concerns about the incidence of antimicrobial resistance.¹⁵⁶ Ontario could support targeted treatments that focus on biologics development relevant to key challenges impacting Ontario's production systems and can be made available in a cost-effective manner to the industry.

5. Address barriers to the adoption of genomics innovations including issues related to data sharing, intellectual property, regulation and public acceptance.



There are several barriers to the adoption of genomics innovations that must be addressed in order to advance Ontario's agriculture and agri-food sector. The most significant barriers include issues related to data sharing, intellectual property, regulation, and public acceptance. There are opportunities for Ontario to focus on issues that are of relevance to the province and do not impinge on federal jurisdiction (e.g., areas of provincial regulatory authority; education and public engagement initiatives) or where Ontario has access to resources and expertise that can enable it to play an important role either independently, or in collaboration with the federal government and other provinces and territories, to advance both regional and national interests.

There was broad consensus during the stakeholder consultations on barriers that may prevent the adoption of genomics technologies in the AAF sector (Appendix 3). Public acceptance was the most agreed-upon issue. Genomics innovations, e.g. CRISPR, provide tremendous opportunities to advance the agriculture and agri-food sector. However, the application of genomics innovations will only succeed if they are deemed to be socially acceptable by the public at large. Genomics-based innovations require proactive communications, engagement, and education to ensure their social license by an accurately informed public. This is especially important for developments related to food and health. For example, despite the tremendous benefits, sound science and assured safety of genetically modified foods, there is a significant anti-GMO movement. Innovations must have public acceptance to be commercially viable. In an era where so much policy relates to technological advances and the increased need and support for genomics-based applications to ensure advancement of Ontario's agriculture and agri-food sector, success in communications and engagement is critical to ensure a more informed public. Perhaps a focus on developing or enhancing nutrient value or other health aspects of foods would help bridge the acceptance barrier.

Other barriers included the ability to manage and share data, the cost and length of the regulatory process for new products, the transfer of research results to stakeholders; research funding and infrastructure challenges, and the need for highly qualified personnel in bioinformatics and funding for multidisciplinary teams. The cost of adopting genomics technologies for some subsectors is also a barrier. Issues related to data sharing, intellectual property, and regulation are complex barriers to the application of genomics-based innovations. Given their interconnectivity, they must be addressed with a view to the impacts of one area on the other. Additionally, consideration must be given to the varying regimes from one jurisdiction to another to ensure the development of commercially viable commodities and products for export markets.

Ontario has access to resources and expertise that can enable it to play an important role both independently as well as in collaboration with the federal government and other provinces and territories, to advance both regional and national interests. Ontario's contribution would be to focus on supporting work on issues relevant to Ontario's AAF sector, working in collaboration with relevant ministries, agencies, and institutions in order to facilitate a coordinated solutions-oriented approach to advance development of the agriculture and agri-food sector.

6. Leverage Ontario's strengths in computational biology and artificial intelligence to accelerate the development and application of agricultural genomics-based innovations.



Big data analysis is becoming increasingly practical (see Subsections 6.2 and 9.4) with the potential to provide remarkable insights into the nature of complex systems. Ontario has strengths in both the public and private sector in computational biology and artificial intelligence that could be leveraged to address issues relevant to the advancement of its AAF sector. Building on those strengths, the Vector Institute for Artificial Intelligence was established in Toronto in 2017 to conduct research and drive the adoption and commercialization of AI technologies across Canada. Machine learning, a powerful form of artificial intelligence, can find patterns in massive data sets and infer computer models of how cells read the genome and generate biomolecules.^{157,158}

A major challenge facing the AAF sector is that there is great variability among commodities and other components of the AAF sector relating to the availability of genomics data and the ability to link this information to metabolism, phenotypic expression, and other attributes in ways that will improve prediction of outcomes and the cost and efficiency of achieving desired outcomes. For example, for major sectors like the dairy, poultry, hog, corn, wheat, and soybean industries, while there is still much to do, there is a wealth of genomics data compared with minor crop and livestock species supported by much smaller industries. Lowering the costs of acquiring and manipulating genomics data will help to level the playing field and should be a continuing priority.

As discussed in Appendix 3 and Subsection 6.2, in addition to systems biology, phenomics was identified as an important opportunity for Ontario. A phenome is the set of physical and biochemical traits belonging to a given organism, and phenomics is concerned with the measurement of change in response to genetic mutation and environmental influences. With technologies for high-throughput phenotyping becoming increasingly available, with conceptual, analytical, and bioinformatic approaches that enable the use of very high-dimensional data advancing rapidly, and with dynamic models that link phenomena across levels—from genes to cells, to organs and through to the whole organism—in reach, it is an opportune time to harness phenomics research in support of Ontario's AAF sector.^{159,160}

11. Synopsis: Ontario, Genomics, and a Sustainable Agriculture and Agri-Food Sector

Genomics will increasingly play an important role in advancing the global agriculture and agri-food (AAF) sector. Focused through the lens of Ontario's dynamic and highly diverse AAF sector, this document describes the many and varied contributions that genomics has made or can make to the sector. It is set in the context of a sustainable AAF system that produces high-quality food and feed as well as industrial bioproducts, using farming and processing technologies that contribute to Ontario's economic development, protects the environment, helps to mitigate and adapt to climate change, and promotes human health, wellness and animal welfare.

In support of a socially and environmentally responsible industry, we examine contributions that genomics can make to production and protection of important commodities, to healthier soils and an understanding of the microbial communities that are essential for this, to food and beverage manufacturing, and to the development of the bioeconomy. We consider the links of the AAF sector to other natural resource sectors, the role genomics can play in helping to understand and preserve biodiversity, and the opportunities to contribute to global food security.

Based on a review of the current status of the Ontario AAF sector and the opportunities for genomics research, translation, and application to the sector, and based on extensive stakeholder consultations, we present a set of recommendations. These recommendations suggest key areas of opportunity for genomics to make important contributions to Ontario's AAF sector over the next decade.

Appendix 1 - Ontario Genomics

Ontario Genomics (OG)[‡] is a not-for-profit organization focused on catalyzing and enabling genomics innovations across key sectors of Ontario's bio-economy including human health, agriculture and agri-food, bioproducts and clean technologies, and natural resources such as mining, forestry and water. A catalyst and convener, we connect ideas, people, and organizations for collaborative investment opportunities in genomics-based research, translation and application aimed at driving economic growth and improving quality of life.

OG's public private partnership programs enable all partners to leverage their funding. Our operations are funded by the Ontario Ministry of Research, Innovation and Science (MRIS) and the federal research funding agency, Genome Canada.

Since its inception in 2000, OG has:

- Raised more than \$1.2B for genomics research in Ontario including \$450M from Genome Canada, \$215M from the private sector and \$110M from MRIS, directly supporting 7,600 R&D jobs.
- Funded over 200 projects, attracting more than 500 partner organizations including national biotechnology and global companies as funding partners, illustrating our national and international competitiveness.
- Helped researchers and startup companies in our project portfolio raise over \$250M in follow-on funding.

As a specialist organization made up of expert staff with experience in academia, funding agencies, startup companies, and multinationals, OG works across the breadth of the innovation ecosystem, while also becoming deeply involved in projects. OG helps researchers position their research ideas for federal and provincial funding, connect with industry partners, work with established companies and startups to advance genomics solutions and educate policy makers, and develop system strategies to make genomics a foundational contributor to Ontario's future health and wellness.

[‡] <http://www.ontariogenomics.ca>

Appendix 2 - Ontario's Agriculture and Agri-Food Sector

As noted in the Introduction, in 2016, the AAF sector contributed more than \$37 billion to Ontario's GDP. Encompassing crop and livestock production, to food processing and manufacturing, the Ontario AAF sector employed approximately 807,000 people in 2016 representing 11.5% of total employment in the province. Demonstrating slow but stable growth, the number of people employed in Ontario's AAF sector grew by 0.6% from 2011 to 2016.²¹

While the AAF sector has been stable at approximately 6% of Ontario's total GDP from 2011 to 2016 there is significant variation in the economic impact between subsectors (Figure 1). For example, the agricultural supplies wholesalers-distributors employed only 4,584 people and contributed \$692 million to GDP whereas the food manufacturing subsector employed 77,681 people and generated over \$9.6 billion dollars in GDP terms.

GDP from Select Agri-Food Subsectors in 2016 (\$ million 2007 dollars)

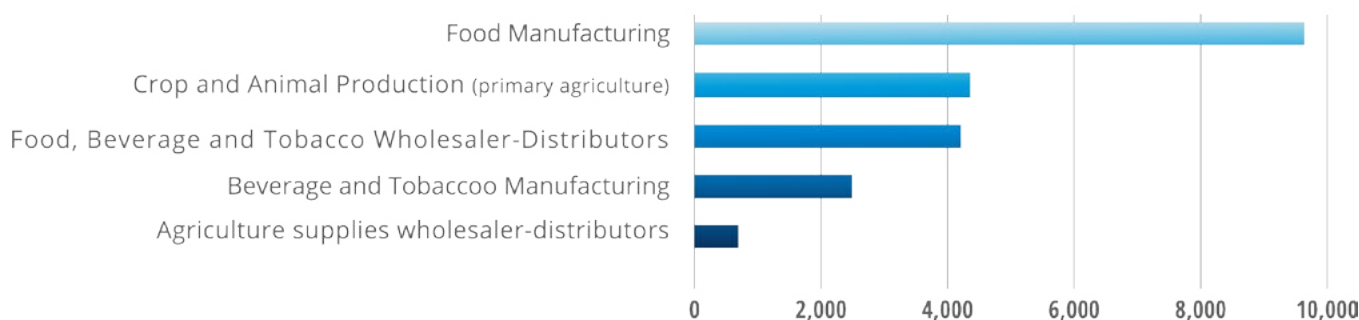


Figure 1: Ontario GDP for the AAF sector in 2016.¹⁶¹

Genomics technologies have transformed aspects of the AAF sector over the past 20 years. Recent advances in these tools, such as rapid and low-cost DNA sequencing, high throughput screening, and our ability to look for rare genetic events, have revolutionized product development in the AAF sector. Methods have moved to prediction-based methods, greatly increasing the rate of product development by accelerating the selection and release of new breeding lines and cultivars. Genomics technologies play an important role in helping the AAF sector compete internationally and remain profitable.

Overall, Ontario is experiencing an increasing trade deficit in AAF sector, with the growth in AAF imports outpacing exports (see Figure 2). To combat this trend and capture more value by processing food domestically, the Ontario provincial government challenged the sector in 2013 to double its annual growth and create 120,000 new jobs by 2020. In 2017 the federal government announced targets for Canadian food exports to grow to \$75 billion annually by 2025, an increase of nearly \$15 billion from current levels. To meet these targets, innovation in the AAF industry will be needed to stimulate economic growth and meet the growing demand for safe, nutritious, sustainable food across the world. Genomics technologies can provide new processes and products to help Ontario producers and manufacturers meet these demands.

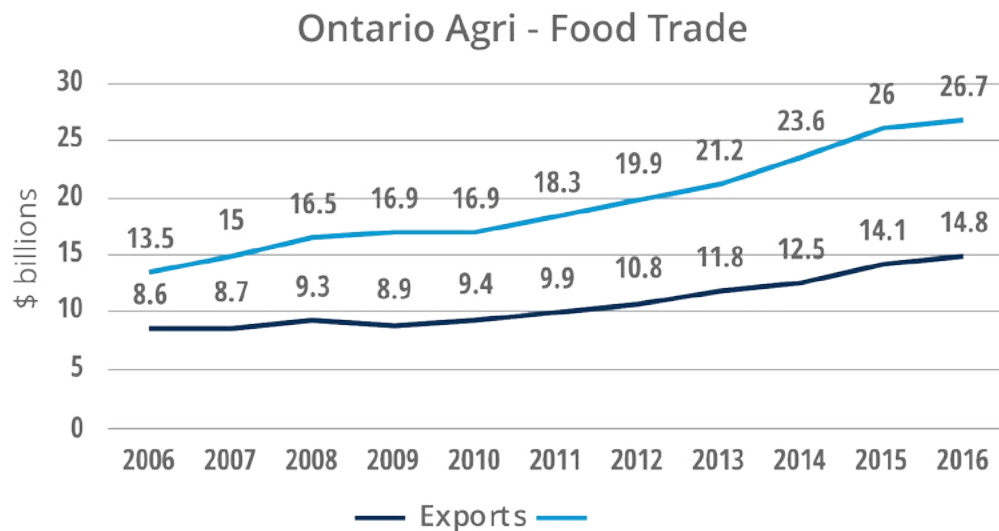


Figure 2: Ontario trade balance 2006-2016. ¹⁶²

Primary agriculture

Primary agricultural production in Ontario is strong in livestock, field crops, and horticulture (including both field and greenhouse crops). Although most farms produce field crops, the dairy sector dominates farm receipts, followed by soybeans, horticultural crops, corn, pork, and poultry (Figure 3). While primary agricultural products are destined for food production, there is a growing demand for agricultural feedstocks in industrial processes, by the fuel ethanol and chemical industries.

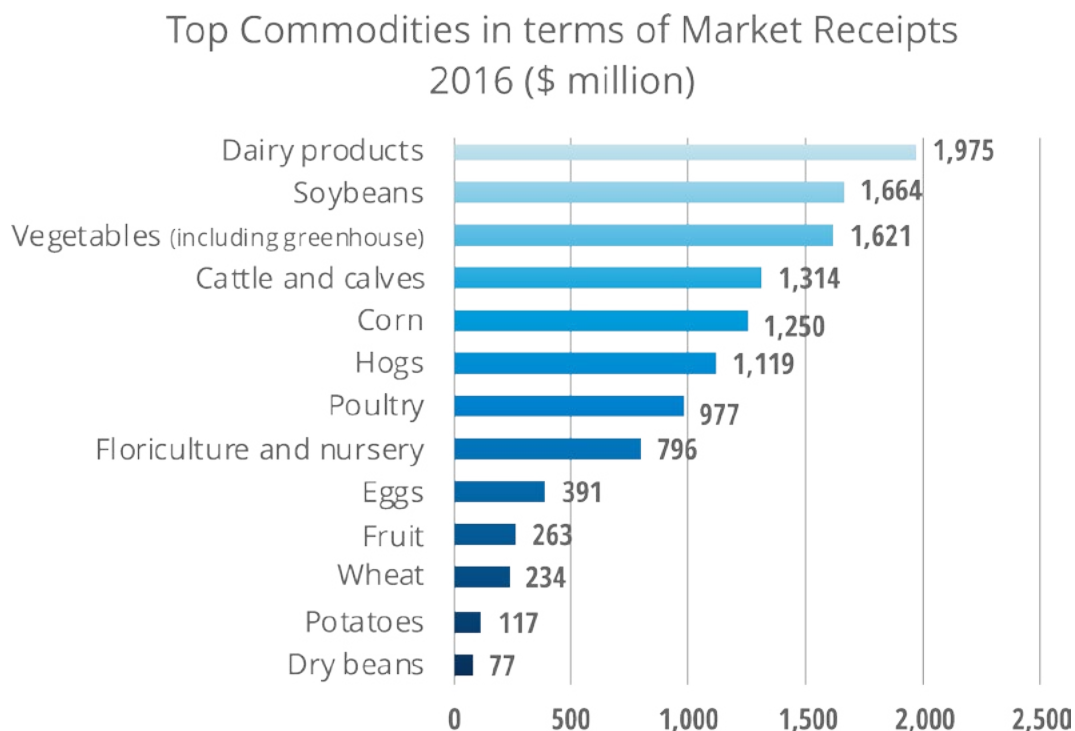


Figure 3: Ontario primary agriculture in 2016 by market receipts. ¹⁶³

Field crops

Field crops are an important segment of the Ontario AAF sector and a main use of the major crops is in animal feed. It is estimated that 77% of soybeans, 45% of corn and 40% of wheat is used for animal feed. Other important uses include further processing for human food (e.g., soybean oil), industrial uses (e.g., corn ethanol), grain export as commodities, and seed production. A breakdown of the area and value of major field crops is shown in Figures 4 and 5.

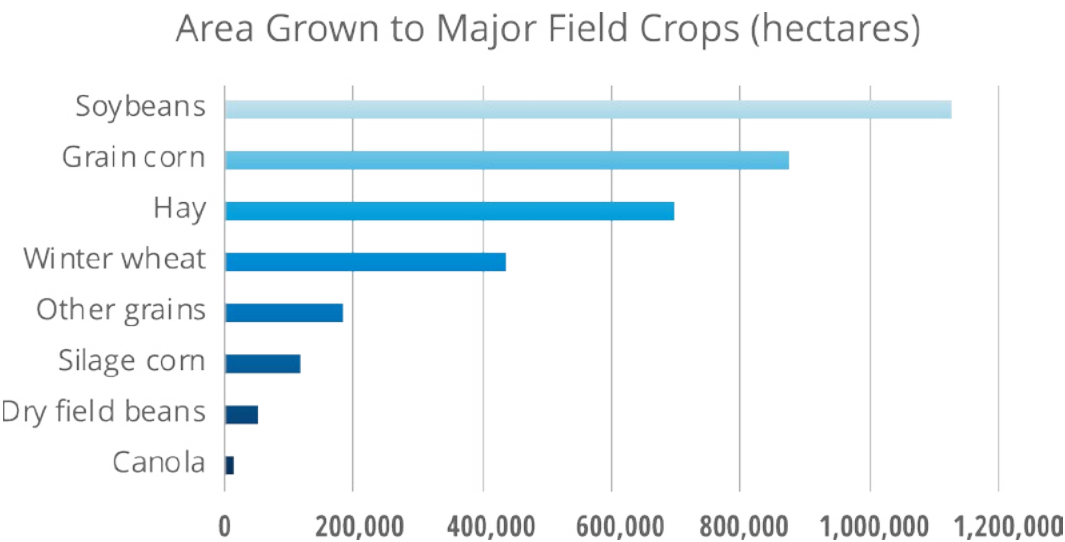


Figure 4. Area Grown to major field crops in Ontario in 2016. ¹⁵⁵

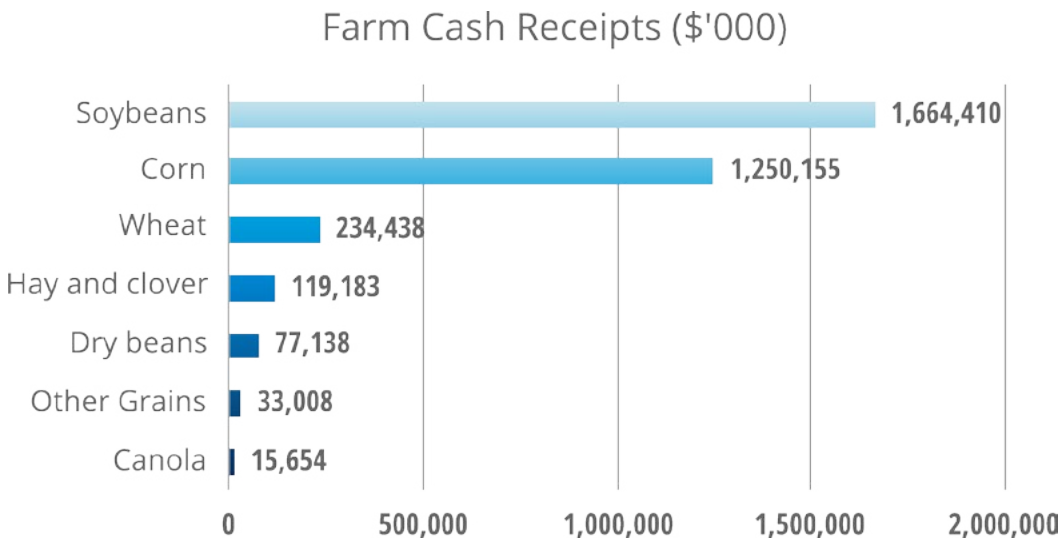


Figure 5. Farm cash receipts from farming operations for major field crops, Ontario, 2016. ¹⁶⁴

Horticulture - fruit & vegetable and ornamentals

The Ontario horticultural sector is well developed in both field and greenhouse production and offers a wide range of fruits, vegetables and ornamental crops.

Figure 6 shows the area (except for protected crops and mushrooms) and value of specified commercial vegetable crops in Ontario for 2016 with the most valuable crops being greenhouse tomatoes, peppers, and cucumbers, and mushrooms with field tomatoes being the most valuable field-grown crop.¹⁶⁵ As noted previously, Ontario's greenhouse vegetable sector comprised 69% of the total harvested area in Canada 71% of Canada's greenhouse vegetables in 2015. In 2016 potatoes were grown on more than 14,000 hectares in Ontario with a farm value of about \$117 million.¹⁶⁶

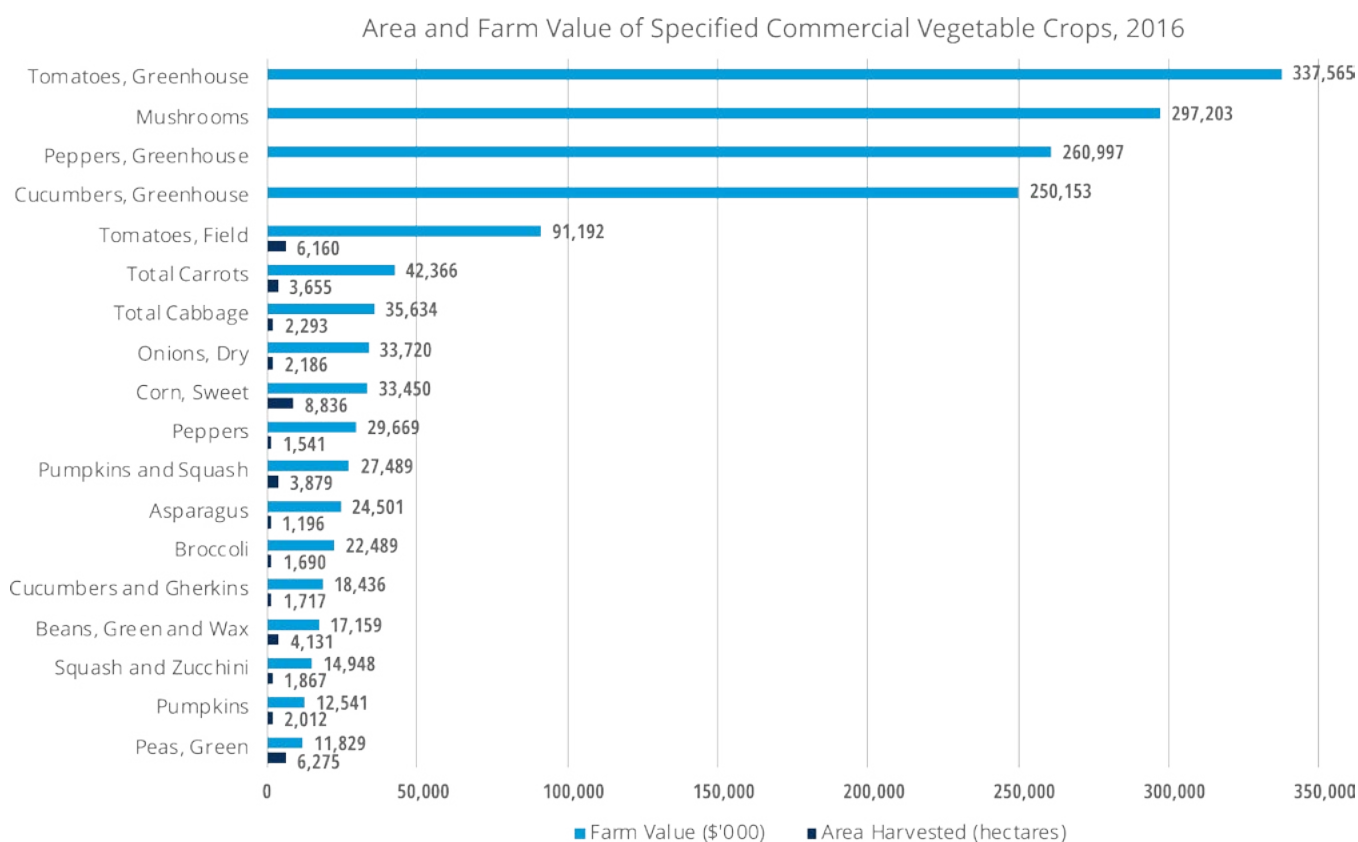


Figure 6. Area (except for protected crops and mushrooms) and value of specified commercial vegetable crops, Ontario, 2016.

Figure 7 shows the area and value of specified commercial fruit in Ontario for 2016 showing that the most valuable crops, wine grapes and apples, also occupy the largest area are, followed by strawberries and peaches.¹⁶⁷

Area and Farm Value of Specified Commercial Fruit Crops, 2016

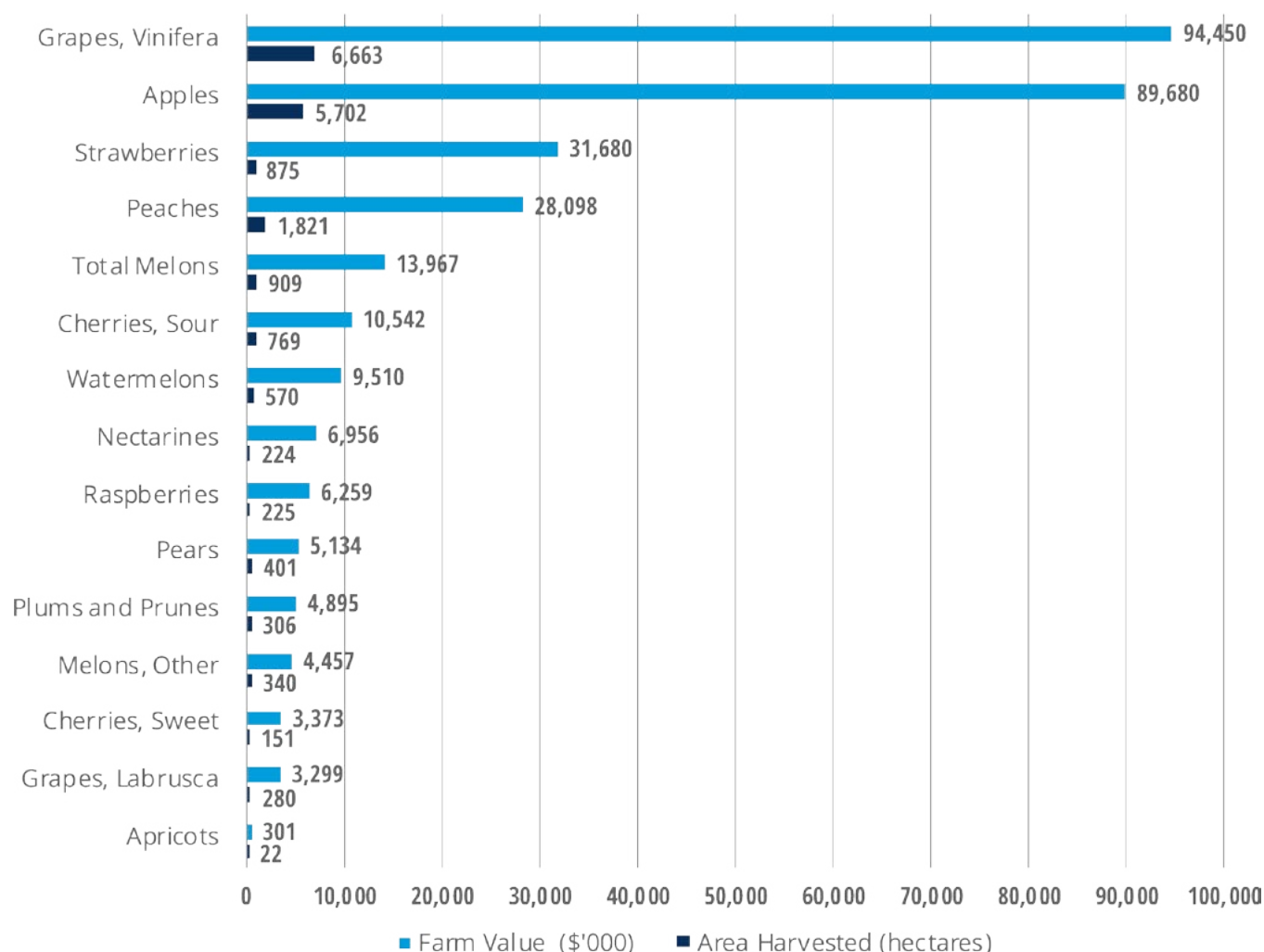


Figure 7. Area and value of specified commercial fruit crops, Ontario, 2016.

Ontario's floriculture, ornamentals, and nursery trades sectors are well established with the total value of ornamental and plant sales exceeding \$790 million in 2016¹⁶⁸ and the total sales of nursery stock and sod exceeding \$340 million in 2016.¹⁶⁹

Livestock

Animal agriculture in the province is dominated by the dairy industry, with beef, hogs, and poultry also playing important roles. Minor livestock species in the province include sheep and goats. The farm cash receipts for livestock and livestock products are shown in Figure 8. Overall the farm cash receipts for the livestock sector exceeded \$6 billion in 2016. Currently in Canada, the poultry, egg and dairy subsectors produce supply managed commodities.¹⁷⁰ As a result, these three sectors experience less price risk and less competition from imports. These factors impact research and innovation commercialization in Ontario, as these subsectors are more likely to take risks by adopting new innovations, compared to non-supply managed subsectors.

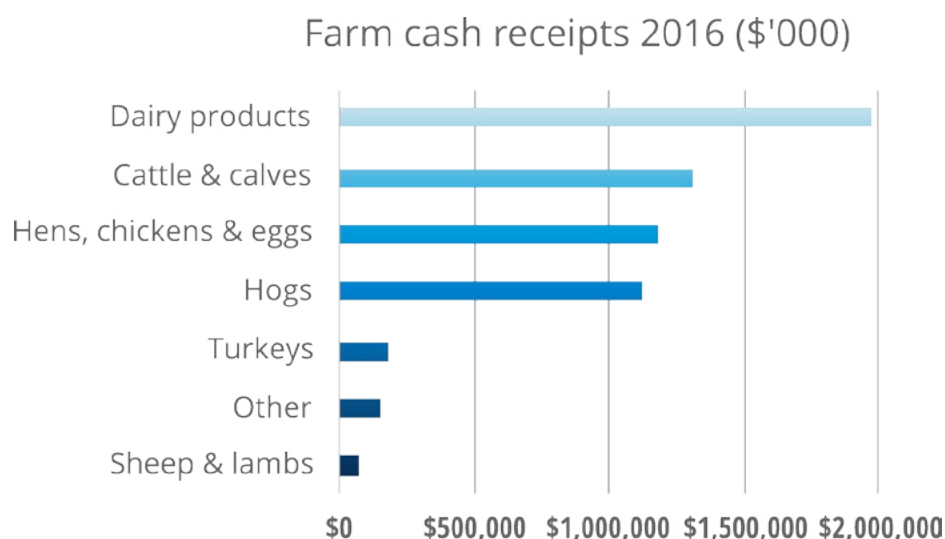


Figure 8: Farm cash receipts for livestock and livestock products for Ontario in 2016.¹⁵⁵

Food & beverage manufacturing

Food and beverage manufacturing is the second largest manufacturing sector in Ontario, with more than \$42 billion in sales in 2015.¹⁷¹ The sector is comprised of a range of business sizes, from large multi-national food companies, down to small businesses producing niche products for diverse domestic and export markets. Ontario employs close to 40 per cent of Canada's workforce in food, beverage and tobacco product manufacturing, and in 2016 Ontario exported almost \$15 billion of agri-food products.¹⁷² Although food processing is conducted across the province, most businesses are in the Greater Toronto Area (GTA), due to its consumer population, workforce availability, extensive transportation infrastructure, and the rich diversity and quality of local agricultural products available.

The majority of Ontario's approximately 3,000 food and beverage processors are SMEs, and often these businesses struggle to invest in research and innovation because of lean margins. New technology adopted by processors often relates to manufacturing and packaging equipment engineering. Genomics can play an important role in several areas of food processing, including fermented foods, food spoilage, food safety, and food authentication. The detection, manipulation and control of microorganisms can improve the productivity and profitability of fermented food production, as well as increase the shelf life and food safety of packaged and fresh foods.

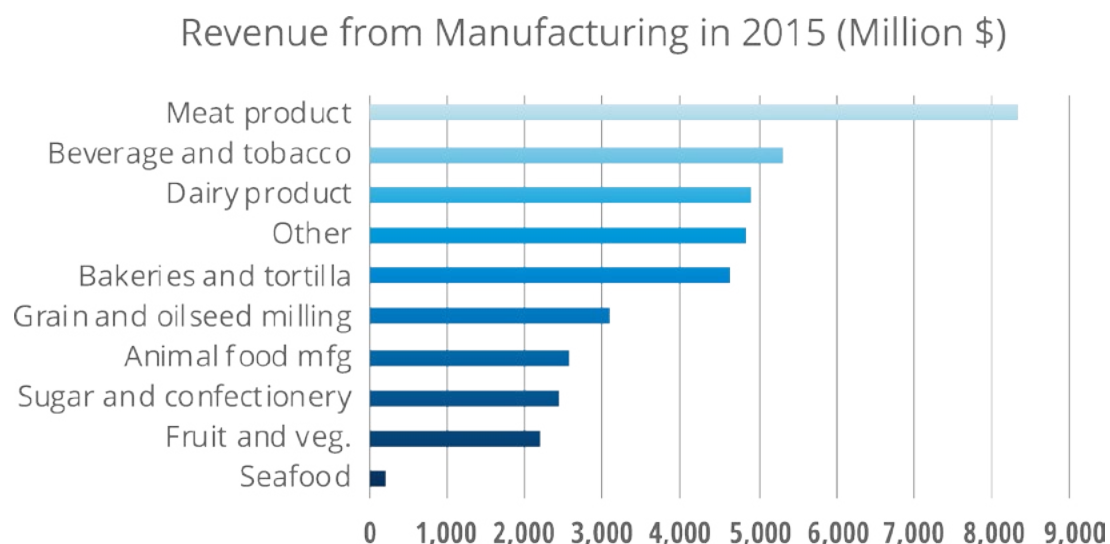


Figure 9: Revenue from Food Manufacturing in 2015.¹⁶²

As shown in Figure 9, the Ontario has core strength in meat product processing. Other important segments of Ontario's food processing are beverage and tobacco, dairy products, bakeries and tortillas, grain and oilseed milling, the manufacture of animal food, sugar and confectionary products, and processing fresh fruits and vegetables. Other small processing types combined, including coffee and tea, syrups, dressings, etc., also make up a large portion of the total industry.

Inputs and services

Throughout the AAF supply chain, producers and food processors are both consumers of inputs and producers of outputs. The estimated size of various input industries in Ontario is shown in Figure 10. The large crop input suppliers of crop protection and nutrition products carry out research in other countries, but there are many smaller Ontario companies developing specialty inputs or technologies that enable traditional inputs to be used differently, such as Vive Crop Protection's nanotechnology encapsulation of pesticides. Feed manufacturers in Ontario also carry out research into animal health and nutrition and these efforts intersect with genomics technologies and breeding selection.

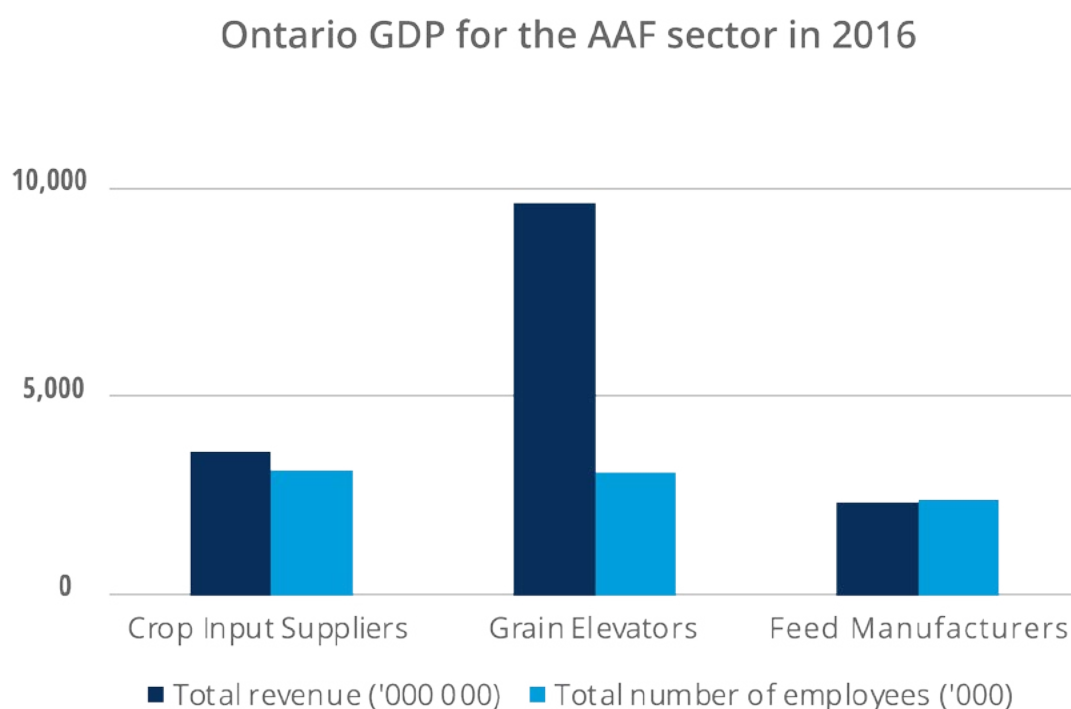


Figure 10: Total revenue and total number of jobs for the Ontario agri-business industry in 2016.¹⁷³

Appendix 3 - Summary of Stakeholder Feedback

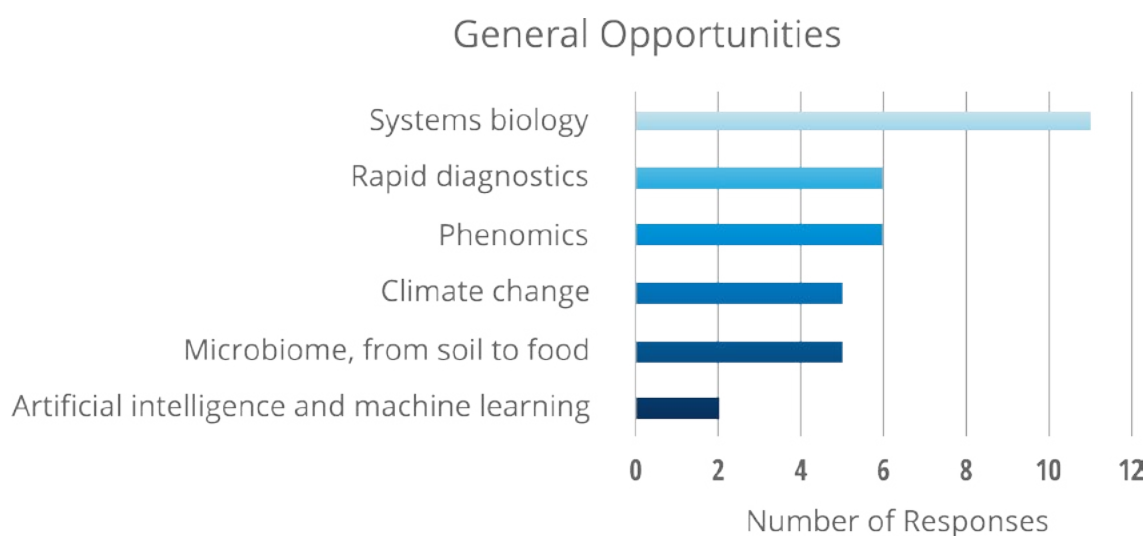
This document summarizes the worksheet and verbal feedback gathered at the Ontario Genomics stakeholder event held in Milton, Ontario September 25th, 2017. Responses have been grouped into categories and the number of respondents counted to approximate the level of agreement/level of priority for that topic.

General Opportunities for Genomic Technologies in Ontario

The largest opportunity in this category was **systems biology**, including the combination of transcriptomics, epigenomics and other 'omics to identify more reliable markers for complex traits and to describe the global regulation of metabolism and physiology. **Phenomics** was another area of opportunity, as the adoption of genomics relies on the description and documentation of phenotypes and this phenotypic data does not exist for all important agricultural species. The advent of high-throughput methods for cataloguing phenotypes via remote sensors will permit the adoption of genomics technologies in more species, more rapidly.

Rapid diagnostics were identified as an area of opportunity all along the value chain – from on-farm, early detection of crop and livestock pests, to the detection of pathogens in food processing and packaging.

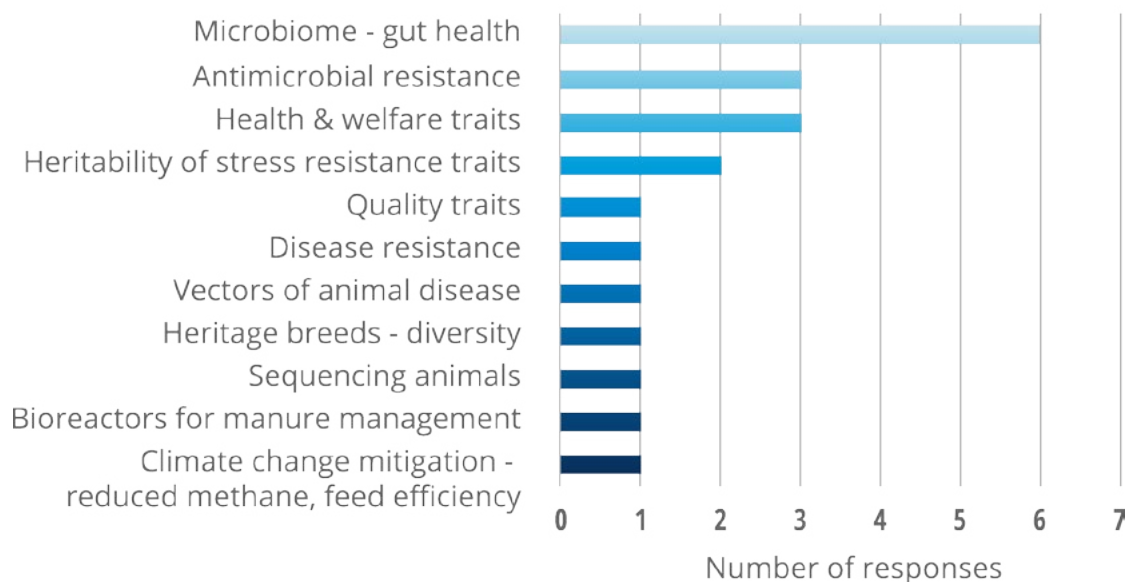
The **microbiome** and **climate change** were also major themes throughout the event, with several responses in both this general category as well as in each specific subsector of agriculture. **Artificial intelligence and machine learning** provide opportunity for the advanced analysis of genomics data across subsectors as well.



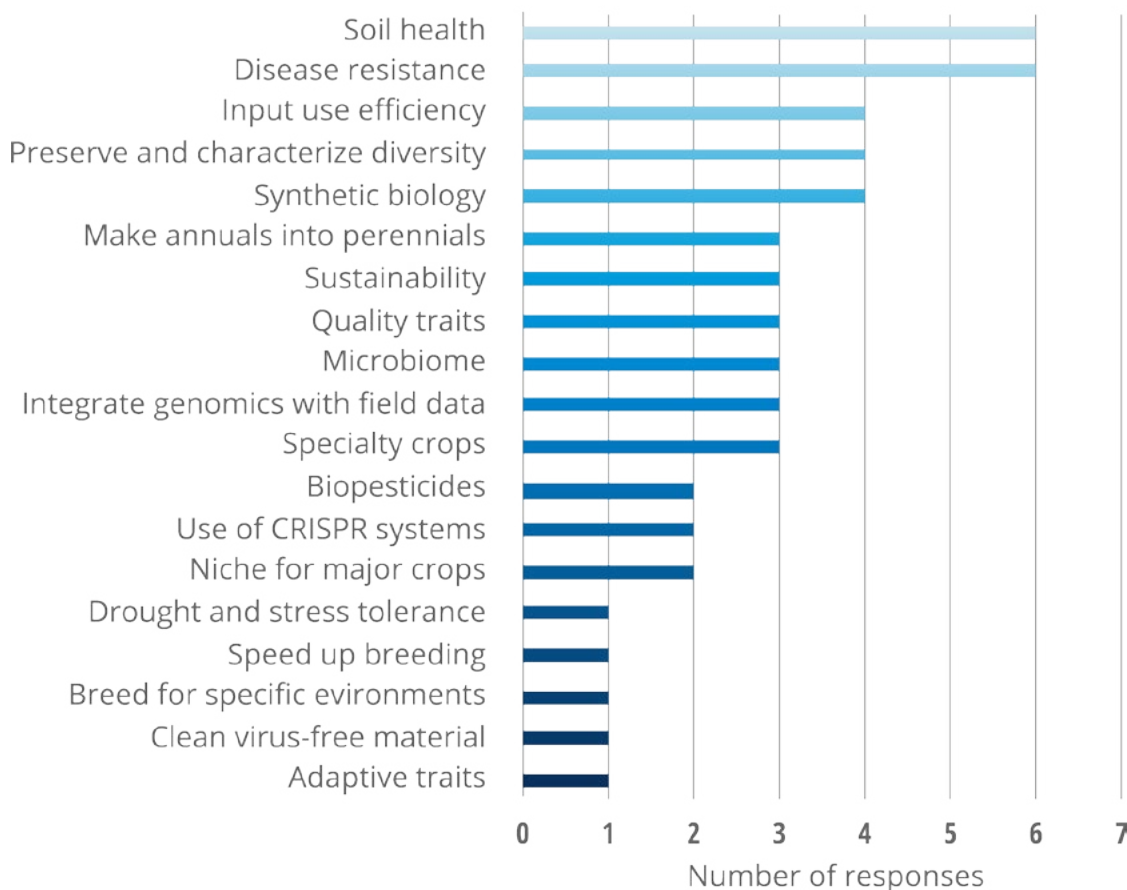
Opportunities for Specific Sectors

Participants identified opportunities within specific sectors throughout the workshop. The major ideas are presented here:

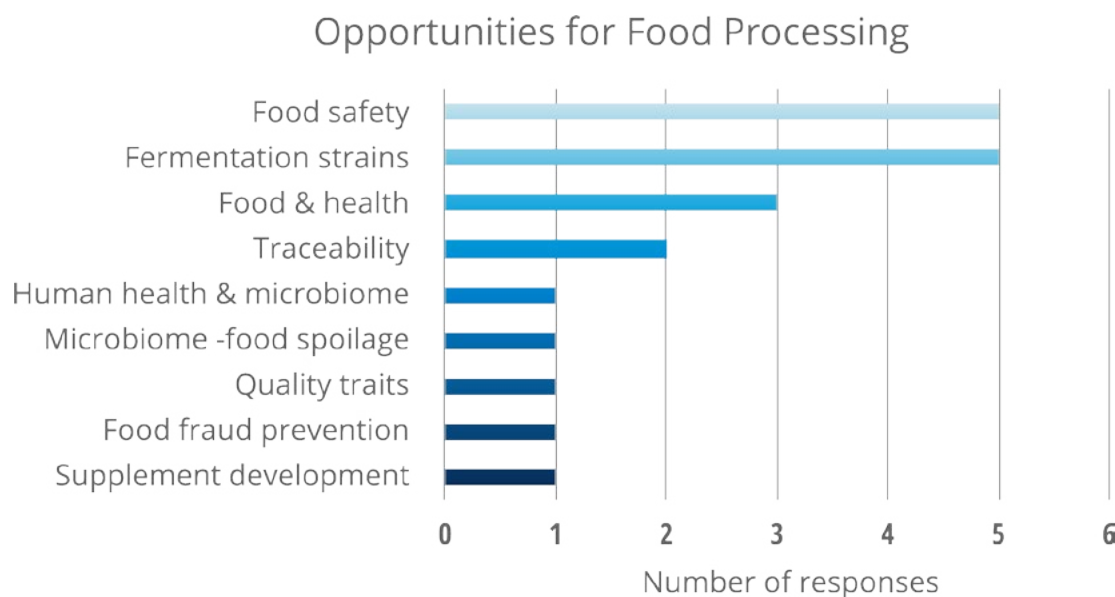
Opportunities in Animal Agriculture



Opportunities in Crop Production



Although not explicitly mentioned at the stakeholder event, implicit in some of the opportunities for crop production and animal agriculture is the ongoing goal to improve yield and performance. “. . . [T]wo ears of corn, or two blades of grass, to grow upon a spot of ground where only one grew before” is as relevant today as it was when Jonathan Swift penned these words in *Gulliver’s Travels* in 1726.



Breakout Group Discussions

In addition to these general ideas, participants were asked to identify opportunities in four different categories. These summarized results are discussed below:

Genomics Datasets and You

In this category, the main topics included how data sets could be combined, shared, and analyzed using cloud-based tools.

Opportunities include:

1. In addition to enhancing product development, these datasets were identified as potential tools to improve the regulatory process. Genomics data, combined with other ‘omics data, could be used to comprehensively characterize a new product, satisfying regulatory requirements as well as building public trust regarding the safety of the product.
2. Sharing data along the value chain: The ability and willingness to share data, right from equipment supplier, to feed/input company to producer precision agriculture data through to food processor, was identified as a way to improve products and processes. There will be limits to the willingness of private industry to share data.
3. Sharing data amongst researchers was identified as a way to reduce duplication of effort, as well as ensure that results can be compared. The challenges for combining these types of research include standardizing data collection across multiple researchers, multiple locations, and different facilities.
4. Selection during the breeding process could be improved by integration of genomics, phenomics, and quality data from multiple environments.
5. Using ‘omics data to capture information to be used by business risk assessment programs.

Quality Traits

The quality traits mentioned by participants included:

1. Extended shelf-life and stability during transport;
2. Nutritional value, biofortification, nutraceuticals;
3. High-value metabolites such as cannabinoids;
4. Regional products for Canadian processors (e.g. ice wine, hops);
5. Meat quality such as mouth-feel;
6. New flavours of plant and animal products;
7. Animal welfare traits such as polled (hornless) cattle and decreased aggression in some species;
8. Wine quality; and,
9. Differentiated egg and milk products.

For these quality traits to be successful, the entire supply chain needs to be involved to ensure there is customer pull for these traits. Standards in measuring the traits and traceability systems also need to be in place to maintain integrity and trust in the supply of these traits. It was noted that consumer preferences for traits must be linked to the economics of production in order to be successful. Some of these quality traits, such as animal welfare traits, may not result in economic benefit to the producer and the value of these traits must be justified.

Climate Change

Participants were asked to identify the challenges and opportunities that could be addressed through genomics technologies. The ideas generated include:

1. Water management and recycling;
2. Decrease pathogen persistence;
3. Enhance animal and plant resilience to climate volatility;
4. Use of controlled environments to intensify production;
5. Reduced inputs;
6. Understanding how climate change impacts contamination of food and feed;
7. Biodiversity linked to resilience;
8. Predict biological shifts in invasive species; and,
9. Generate diversity for change in environments (e.g. high CO₂).

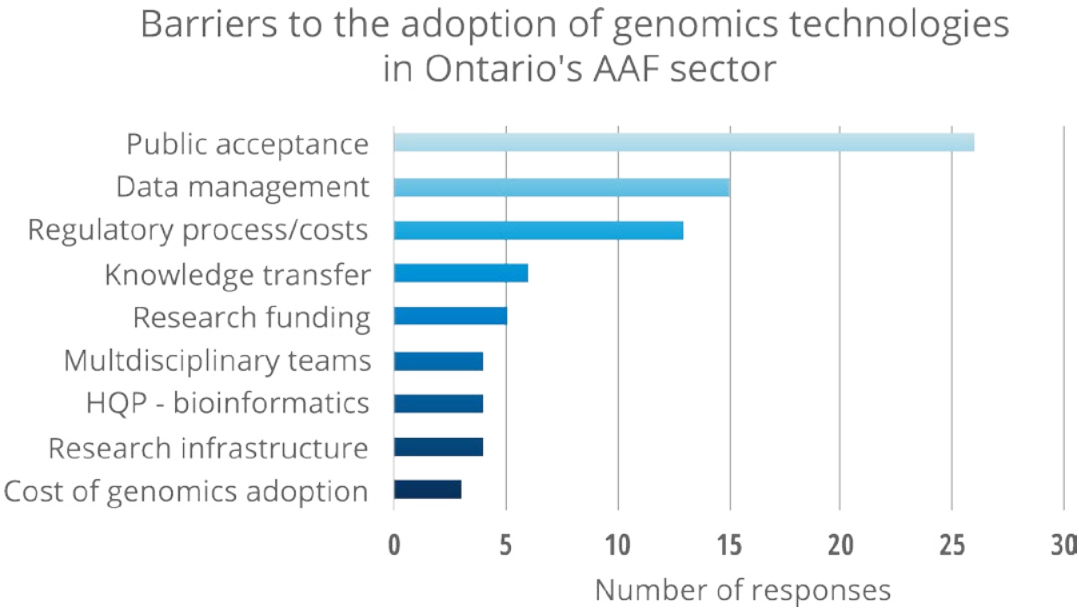
From Genomics to Fork

Participants were asked to identify opportunities for genomics in the food processing sector as well as enabling programs or connections that would be necessary for these technologies to have impact.

1. Animal health risk assessment organization – an integrated North American bioinformatics infrastructure related to epidemiology of animal disease;
2. Rapid methods to detect food fraud and product origin;
3. Rapid methods to detect mycotoxins;
4. Food allergen detection, removal from food products;
5. Decrease pathogen persistence in food processing environment;
6. Identify spoilage microbes to enhance product stability; and,
7. Enable establishment of food safety plans that are compliant with regulatory programs.

Barriers

Broad consensus was reached as to the common barriers that may prevent the adoption of genomics technologies in the AAF sector. Public acceptance was the most agreed-upon topic of the stakeholder workshop. Other barriers included the ability to collect, store, share and analyze data in a standard way and the cost and length of the regulatory process for new products. Other common barriers were at the level of research, including the transfer of research results to stakeholders, research funding and infrastructure challenges, as well as the need for HQP in bioinformatics and funding for multidisciplinary teams. The cost of adopting genomics technologies for some subsectors is also a barrier, as it is costly for individual producers to adopt genomics into their on-farm breeding efforts.



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