VISTA
SCIENCE AND TECHNOLOGY
ONTARIO • CANADA

INNOVATION POSITIONING ASSESSMENT

Agricultural System Modelling Tools at the Intersection of Policy, Sustainability, and Technology Adoption

Innovation Positioning Assessment on Modelling Tools at the Intersection of Agriculture, Policy, Sustainability and Technology Adoption

June 2025

Prepared For: Just Transitions in Agri-Genomics Research Team

Prepared By: Allison Clark and M. A. Lemay
VISTA Science and Technology

VISTA Science & Technology
Putting Research Into Action

Table of Contents

Innovation Positioning

The Innovation Positioning assessment is one of the tools in VISTA's Innovation Positioning Framework (IPF). The IPF evaluates and positions research and technology (agri-innovations) to support development, commercialization, acceptance and adoption. The IPF provides evidence-based advice and guidance for strategically positioning research and technological innovations.

The Innovation Positioning tool is an early-stage, high-level assessment of research or technological innovations. It strategically positions research and technology based on four key positioning criteria: scientific/technical, market, stakeholders and impacts. The objective of the Innovation Positioning is to provide evidence-based advice and recommendations for positioning research and technological innovations for successful commercialization and adoption.

Description of the Research

The Just Transitions in Agri-Genomics research project is focused broadly on the interconnectedness between agricultural policies, technology adoption, and sustainability. Using an interdisciplinary and systems-based approach, the research seeks to examine the social elements of policy and technology adoption. This work will offer insights into how to best leverage agricultural technologies (e.g., cellular agriculture and vertical farming) for environmental sustainability, without compromising economic or social sustainability. In other words, the work will produce insights to ensure a just transition to a sustainable and technology driven agricultural system.

As a part of this research, the Just Transitions in Agri-Genomics ICT is working to develop modelling tools that will support agricultural planning and policy. Modelling tools draw upon three phases of research. The first phase includes modelling the impacts of future climate scenarios on agricultural landscapes, focusing on seven economically important crops in British Columbia (celery, broccoli, cauliflower, kale, strawberries, lettuce, and cabbage). The second phase of the research includes stakeholder engagement, whereby farmers are being surveyed to understand their openness to adopting new technologies (e.g., vertical farming or functional genomics) and/or switching crops under specific climate scenarios. The third phase includes modelling the impacts of policy scenarios, such as incentive programs, on agricultural technology adoption and sustainability outcomes. This research will contribute to the development of two modelling tools: one will simulate the impacts of climate change scenarios on agricultural landscapes, while the other will simulate the impacts of policy scenarios on technology adoption and sustainability outcomes. Through partnership with i-Open technologies, these modelling tools may be integrated into the pre-existing Agrilyze platform, offering commercialization potential.

Description of Niche

Given the multifaceted and complex nature of this research, it would be challenging to provide an in-depth innovation positioning assessment of both modelling tools being generated for the project (i.e., modelling tools that simulate the impacts of different climate scenarios on agricultural landscapes, and modelling tools that simulate the impacts of different policy scenarios on technology adoption and sustainability outcomes). As such, this assessment focuses specifically on modelling tools that simulate the impacts of policy scenarios on technology adoption and sustainability outcomes. When possible, the report offers broad insights that can support the commercialization of both modelling tools.

Strategic Positioning Recommendations

It is recommended that the Innovation Challenge Team (ICT) consider novel technical advances in the research and patent literature, including artificial intelligence (AI), machine learning (ML), and digital twins. AI, ML, and digital twin technologies are becoming increasingly prevalent in the research and patent literature (See Global Research Review; See Global Patent Review). This includes the incorporation of artificial intelligence and machine learning techniques into pre-existing modelling methodologies, such as agent-based modelling or system dynamic modelling (See Global Research Review; Sánchez et al., 2022). Moreover, recent patents are leveraging causal AI and digital twin simulations to uncover the relationships between environmental, economic, and policy variables within agri-food systems (e.g., CN119671707A). It is important that the ICT consider integrating novel technologies (i.e., AI, ML, and digital twins) into the modelling tool(s) to remain competitive in the field.

It is recommended that the ICT stay apprised to international and national standards related to digital agriculture. Standardization of modelling approaches is becoming increasingly important, especially as novel technologies like AI and ML are being integrated into agri-food system modelling approaches (Sánchez et al., 2022). One example of standardization efforts is ISO Technical Committee 347 Data-driven agrifood systems. This work is focused on addressing interoperability challenges in a variety of areas, including sustainability models, metrics and data in agrifood systems.[1] The ICT may benefit from participating in this international standards development initiative through the Canadian Mirror Committee, which is managed the CSA Group.[2]

It is recommended that the ICT develop collaborative research partnerships to help expand the regional scope of the modelling tool(s). Expanding the modelling tool beyond the Fraser Valley, and beyond British Columbia can help attract additional end-users and support commercial success. A way to accelerate regional expansion is through collaborative partnerships with other researchers developing agri-food system modelling tools in Canada. There are two notable researchers working on similar initiatives in Canada. Dr. Hassini of McMaster University is leading the Farming Analytics and Resilience Modelling (FARM) project, which seeks to model the impacts of economic, social, policy, and climatic scenarios on agricultural systems, including the adoption of digital technologies.[3] Dr. Adamchuk of McGill University is leading a project that applies a meta-systems model to inform farm management and agri-environmental policy design. By partnering

[1] https://www.iso.org/committee/9983782.html#:~:text=ISO/TC%20347%20%2D%20Data%2Ddriven%20agrifood%20systems.
[2] https://www.csagroup.org/standards/areas-of-focus/agriculture-agri-food/#:~:text=CSA%20Group%20has%20established%20advisory%20groups%20to,and%20expertise%20and%20contributing%20to%20global%20standardization. ;
[3] https://www.nserc-crsng.gc.ca/ase-oro/Details-Detailles_eng.asp?id=777789

with these researchers and/or other researchers that are modelling agri-food systems across Canada, the project may be able to scale more rapidly.

It is recommended that the ICT develop a marketing and communications strategy that showcases the value-add of the modelling tool(s) and why end-users should pay for the tool(s). There are several agricultural system modelling tools that are free and publicly available (See Commercial Solutions). The Food and Agriculture Organization (FAO) of the United Nations alone offers over twenty software models that can be downloaded and used for free to assist policy decision, research projects, and field decisions.[4] Many of these tools are funded by government or intergovernmental initiatives for public good rather than commercial profits. While there are a number of free tools available, none of these tools specifically simulated the impacts of different policy scenarios on ag-tech adoption, presenting a unique market gap that the ICT can fill (see Commercial Solutions). This unique value offering could present a competitive advantage over other free tools, which could be articulated in a marketing campaign. In all, it is prudent that the ICT develop clarity surrounding the value that the modelling tool(s) will provide to help justify costs associated with the tool.

It is recommended that the ICT consider diversifying the value offering of the modelling tool(s) to attract additional end-users. The end-users interested in agri-food *system* insights are limited and may be less likely to pay for the tool, as described above (see Niche Overview). Greater impact may be achieved by diversifying the value-offering to other end-users. This could include offering tailored simulations for technology developers interested in measuring adoption rates and/or understanding the impacts of their technology on sustainability outcomes. The ICT can assess the feasibility of diversifying the value offerings of the modelling tool(s).

[4] https://www.fao.org/land-water/databases-and-software/en/

Summary of Findings

Within the past five years, there has been a significant uptick in relevant research activity, including more sophisticated modelling approaches that incorporate quantitative and qualitative analyses into policy scenario generation (see Global Research Review). Much of the research focuses on modelling the impacts of policy scenarios on sustainability outcomes (e.g., GHG emissions, water management and irrigation, and soil health), rather than modelling the impacts of policy scenarios on technology adoption (see Global Research Review). This general trend holds true in the patent literature (see Global Patent Review) and in the marketplace (see Commercial Solutions), highlighting a gap in the body of knowledge and in the market.

Patenting activity on agricultural modelling tools at the intersection of policy, sustainability and/or technology adoption has increased substantially within the past ~10 years, with a significant uptick in 2024 (see Global Patent Review). An increasing number of patent applications and patent publications incorporate AI, ML, and digital twin technologies into their invention, highlighting technical advances in the field. Interestingly, many of the relevant patents are owned by academic institutions or researchers, rather than private companies, suggesting that the field is highly academic.

With a rise in technical innovations, including AI, ML, digital twins, and cloud computing, the global market value of modelling tools is growing rapidly (see Niche Overview). This growth is exhibited in market research on the software simulation market[5], decision support system market[6], digital twin market[7], and 3D modelling and mapping market.[8] While these broad markets are growing, much of this growth is being experienced in aerospace and defence, energy and utilities, and business management, rather than agriculture (see Niche Overview).

Most of the modelling tools that assess dynamic agricultural systems are funded by government or intergovernmental initiatives (e.g., the United Nations) in support of policy and sustainability initiatives (see Commercial Solutions). These tools are free and publicly available. While free tools are available, the modelling tool(s) being developed by the Just Transitions in Agri-Genomics research team have unique value-propositions that present competitive advantages. For example, the focus on modelling the impacts of policy scenarios on technology adoption is a novel approach not widely available on the market. With this market gap and internal strengths, such as the partnership with i-Open Group, the ICT has a competitive advantage in the marketplace.

Given the system level nature of the modelling tool(s) being developed by the Just Transitions in Agri-Genomics research team, there are diverse stakeholders to consider. Stakeholder groups include potential end-users, investors and funding agencies, Indigenous communities and organizations, and agricultural media (e.g., journalists and podcasters). Each group may play an important role in the project's success at varying stages of development.

[5] https://www.marketsandmarkets.com/Market-Reports/simulation-software-market-263646018.html
[6] https://www.grandviewresearch.com/industry-analysis/decision-support-system-market-report
[7] https://www.researchandmarkets.com/reports/5936063/digital-twin-market
[8] https://www.fnfresearch.com/3d-mapping-and-modeling-market

Innovation Positioning SWOT

A SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) is a critical component of an innovation positioning assessment. It provides a structured, strategic framework for assessing an innovation, based on factors that can influence its success in terms of development, commercialization, acceptance and adoption. The SWOT analysis looks at both positive (strengths, opportunities) and negative (weaknesses, threats), internal (strengths, weaknesses) and external factors (opportunities, threats) (Table 1). The SWOT analysis offers insights for strategically positioning an innovation as scientifically and technically sound, commercially viable, and socially acceptable.

Table 1. Innovation Positioning SWOT Analysis

SWOT Analysis	
Strengths	• The innovation is **aligned with market demands** for simulation software and modelling tools that support environmental sustainability decision making and planning. The software simulation market[9], decision support system market[10], digital twin market[11], and 3D modelling and mapping market[12] are all expected to experience rapid growth within the next decade, driven in part by technical advancements and an increasing interest from government and industry for solutions that drive resource efficiency and sustainability (See Niche Overview; Table 6). • There is very little research and patenting activating on modelling tools, approaches, or methodologies that specifically simulate the impacts of policy scenarios on technology adoption in agriculture. This is reflected in the marketplace, with no marketed tools advertising this specific capability. This innovation therefore **fills a gap in the scientific literature and in the marketplace**. • Multi-year funding and support from **Genome Canada** may give the project team a competitive advantage over other researchers and innovators, who may not have extensive funding. • The project team is supported by **knowledge mobilization** expertise from Genome Canada's Ag-ACT team, who can help the ICT in engage with diverse stakeholders (see Stakeholder Positioning; Table 7) and increase research impact. • The partnership with **i-Open Group's Agrilyze platform** can be leveraged to support commercialization and market expansion.
Weaknesses	• Based on the current design specifications of the modelling tool(s), there is a **limited pool of end-users**. The system-level policy and sustainability insights offered by the tool will be most beneficial to government, researchers, non-profits, and agricultural advisors. On the other hand, industry, including farmers and ag-tech companies, are less likely to be direct end-users of the modelling tool. The limited number of end-users could constrain the ability to grow (see Niche Overview; Table 6 and Stakeholder Positioning; Table 7).

[9] https://www.marketsandmarkets.com/Market-Reports/simulation-software-market-263646018.html
[10] https://www.grandviewresearch.com/industry-analysis/decision-support-system-market-report
[11] https://www.researchandmarkets.com/reports/5936063/digital-twin-market
[12] https://www.fnfresearch.com/3d-mapping-and-modeling-market

Opportunities	• **Advances in artificial intelligence (AI) and machine learning (ML)** are driving market growth for simulation software and modelling tools by increasing data processing power and accuracy.[13] While AI-augmented modelling approaches (e.g., AI-augmented agent based models) are on the rise, there remains a lack of standardization and validation of methods utilized in the literature (See Global Research Review; Sánchez et al., 2022). There is an opportunity to build upon AI-augmented modelling approaches and develop a novel AI-augmented approach for agricultural system modelling that is aligned with standards being developed for data-driven agrifood systems.[14] • i-Open Group is a Canadian leader agricultural monitoring, detection, analysis, and prediction. By leveraging the partnership with i-Open Group, there is a unique opportunity to be a **leader in the Canadian market**. • There is an opportunity to offer **paid training** to teach end-users how to utilize the tool to inform policy decisions, technology development decisions, or investment decisions. • There is an opportunity to **collaborate with other researchers** that are developing agri-food system modelling tools in other jurisdictions in Canada. This could help to expand the tool more rapidly, and offer more functionality based on research partner's specialties. Potential collaborators include Dr. Adamchuk of McGill University and Dr. Hassini of McMaster University, both of which are leading projects on agri-food system modelling.[15] • There is an opportunity to **diversity the value-offerings of the modelling tool(s)** to expand the potential pool of end-users. For example, ag-tech solutions developers may be interested in leveraging the tool(s) to simulate technology adoption under specific policy or climate scenarios and/or simulate the sustainability outcomes/environmental benefits of their technology. Technology developers may be especially interested in this value offering under new regulations that necessitate proof of environmental benefits.[16]
Threats	• There are several **free tools** that are open-source and publicly available.[17] These tools are often developed with government funding to support government initiatives and/or public good. Because free agri-food system tools are available, end-users may have difficulty justifying paying for the modelling tool(s). • Challenges related to **cybersecurity, data privacy, and data ownership** could limit the scalability and success of the modeling tool(s).[18] These concerns have become especially prevalent with the adoption of cloud-based platforms, which operate remotely and have additional security risks.[19]

[13] https://www.marketsandmarkets.com/ResearchInsight/emerging-trends-in-simulation-software-market.asp
[14] https://www.iso.org/committee/9983782.html#:~:text=ISO/TC%20347%20%2D%20Data%2Ddriven%20agrifood%20systems
[15] https://www.nserc-crsng.gc.ca/ase-oro/Details-Detailles_eng.asp?id=777789 ; https://www.nserc-crsng.gc.ca/ase-oro/Details-Detailles_eng.asp?id=782526
[16] https://www.blg.com/en/insights/2024/07/false-advertising-and-greenwashing-bill-c-59-changes-to-competition-act#:~:text=Bill%20C-59%2C%20The%20Fall,environmental%20benefit%20claims%20(greenwashing)
[17] https://www.fao.org/land-water/databases-and-software/en/ ; https://www.climateinteractive.org/en-roads/ ; https://www.ifpri.org/project/ifpri-impact-model/ ; https://www.fao.org/in-action/mosaicc/en/
[18] https://www.marketsandmarkets.com/Market-Reports/simulation-software-market-263646018.html
[19] https://www.marketsandmarkets.com/Market-Reports/simulation-software-market-263646018.html

The SWOT analysis summary (Table 2) provides strategic insights on how strengths and opportunities can be leveraged to address weaknesses and mitigate threats.

Table 2. SWOT Analysis Summary – Strategic Insights

	Weaknesses	**Threats**
Strengths	• The ICT can leverage the fact that the modelling tool(s) fill a unique market gap (i.e., modelling ag-tech adoption under different policy scenarios) and get buy-in from stakeholders. • The partnership with i-Open Group may help to diversify and expand end-users by tapping into existing relationships and client networks. • The ICT can leverage knowledge mobilization expertise to disseminate insights from the modelling tools and/or share the value of the modelling tools to prospective end-users. • Paid training could present an opportunity to engage end-users and stakeholders with the modelling tool in a more affordable manner, rather than larger software licensing costs or subscription models. Training could also enhance the value of the modelling tools for end-users, providing justification for costs.	• While free modelling tools exist, no free modelling tools exist that specifically model the impacts of policy scenarios on ag-tech adoption. This unique value offering can be leveraged to market the tool in spite of free modelling tools currently available. • Technical expertise and resources within the ICT and industry experience within i-Open Group may be leveraged to help develop cybersecurity protocols and ease concerns relating to data privacy and data ownership.
Opportunities	• While there is a limited pool of end-users, there is also limited competition in the Canadian market for these end-users. The ICT can leverage its competitive advantage in the Canadian market to capture a larger share of end-users. • The ICT has an opportunity to diversify the value offering of the modelling tool to capture additional end-users, including industry players in agriculture and ag-tech.	• Free modelling tools on the market are designed to provide system-level insights – typically to policy makers. Meanwhile, tools on the market that have paying customers are generally more specific in nature, offering precise insights for a particular farm, for instance. The ICT has an opportunity to diversify its value offering so that they can attract more customers willing to pay for the tool. This may include offering simulations for individual farms or ag-tech firms.

Science & Technology Positioning

Science and technology positioning is critical for successfully moving research and technological innovations through development, commercialization, acceptance and adoption. Without a clear understanding of where an agri-innovation stands within the global research and patent landscape, even the most promising ideas can face unexpected challenges and barriers. Assessing global research and patenting activity provides insights into the competitive landscape and evidence for making informed decisions about research priorities, intellectual property and commercialization strategies. Science and technology positioning guides innovations toward real-world impact, commercial success, and wide-spread adoption.

Global Research Review

Reviewing global research is critical for positioning innovations to advance knowledge, leverage competitive advantage and drive development, commercialization, acceptance and adoption. The global research review summarizes research activity, including trends and key focus areas. The research included in Table 3 is a representative, rather than exhaustive, sample of relevant or related research.

This Global Research Review focused on modelling tools and approaches that simulate agricultural policy scenarios and their impacts on technology adoption and environmental sustainability. Key words on modelling approaches, including "ex-ante," "agent-based modelling," "participatory modelling," and "decision support system," were paired with key words related to policy scenarios, sustainability outcomes, technology adoption, and agriculture/farming. These key words were used to generate search strings for searching on Google Scholar, DOAJ, the Canadian Agriculture Library, the USDA National Agricultural Library, and NSERC (Canada).

A total of 32 studies were included for analysis based on their relevance to the modelling tool being developed by the Just Transitions in Agri-Genomics research team. These studies were used to generate insights on general trends in the literature, including research activity, geographical distributions of the research, and key trends. Upon completing a high-level thematic analysis, the literature was further sorted based on publication date and applicability. This resulted in a shortlist of 10 studies, including eight publications and two recently awarded NSERC grants (Table 3). These studies were further analyzed for in-depth insights related to methodological approaches, sustainability topics, and research gaps and opportunities.

General Trends in the Literature

Relevant studies date back to the early 2000s, where research on socioeconomic and biophysical modelling in agriculture began increasing in popularity. This includes early research activity in Canada, with a 2001 study by Agriculture and Agri-Food Canada (AAFC) simulating the environmental impacts of policy and program scenarios on nitrogen leaching. There was an increase in relevant research activity in the 2010s, including research focused on modelling interconnections between socioeconomic and biophysical processes, and research focused on modelling the impacts of agricultural policies on environmental impacts and farming system changes. Within the past five years, there has been a significant uptick in relevant research activity, including more sophisticated modelling approaches that incorporate quantitative and qualitative analyses into policy scenario generation. The body of literature is international in nature.

Much of the research focuses on modelling the impacts of policy scenarios on sustainability outcomes. Common sustainability topics include water management, greenhouse gas emissions, and soil health. Literature related to modeling policy scenarios for improved irrigation and water resource management are especially common in arid regions, including China, Iran, and parts of the European Union (e.g., Spain). Meanwhile, research related to the impacts of different policy scenarios on greenhouse gas emissions and soil health in agriculture are more common in places like North America, such as Texas.

In comparison to studies modelling the impacts of policy scenarios on sustainability outcomes, fewer studies have been done on the impacts of policy scenarios on technology adoption. Some research has been done on the impacts of policies on the adoption of precision agriculture technologies, conservation tillage technology, and "smart farming" more broadly. However, this is a newer area of focus, with a slight uptick in research related to agri-food tech adoption within the past five years.

Modelling Approaches: Agent-Based Models, System Dynamics, and Positive Mathematical Programming

A variety of modelling/simulation approaches are utilized in the literature. Common methodological approaches include Agent-Based Models (AMB), System Dynamics (SD) models, and Positive Mathematical Programming (PMP). In some cases, these models are combined with biophysical, and spatial modelling to infer agricultural system dynamics, including insights for agricultural policy and planning. For example, some studies integrate Geographic Information Systems (GIS), Life Cycle Assessments (LCA), and ABM approaches. Other research describes integrating machine learning and artificial intelligence methodologies into modelling approaches.

The most common approach to modelling the impacts of different policy scenarios on agricultural technology adoption and sustainability outcomes are ex-ante agent-based models (ABM) (Sánchez et al., 2022; Sun et al., 2022; Huber et al., 2023; Coronese et al., 2024). ABM is commonly used to assess the interactions of heterogenous behaviours among agents (e.g., farmers, households, or firms) and system-level priorities and scenarios. Most of the literature uses traditional, rule-based, probabilistic ABM techniques (Sun et al., 2022; Huber et al., 2023; Coronese et al., 2024). For example, Huber et al. (2023) integrated a bioeconomic optimization model into an ABM that simulated Swiss farmer's adoption of precision nitrogen technologies under different policy scenarios. Meanwhile, Coronese et al. (2024) used a model called "AgriLOVE", which incorporated land-based and ABM approaches to assess transitions between conventional and sustainable farming under different soil degradation constraints in Italy. Similarly, Sun et al. (2022) incorporate GIS, ABM, and machine learning-based climate forecasts to simulate the diffusion of beneficial water management practices in Canada. These examples underscore the applicability and diversity of ABM in modelling complex socioeconomic and environmental systems.

An emerging field of ABM research is the integration of artificial intelligence (AI) algorithms with ABM. While most of the reviewed literature utilizes rule-based ABM, a recent systematic review by Sánchez et al., 2022 highlights a growing field of AI-augmented ABM in the sustainable agriculture literature. Sometimes referred to as "intelligent agent-based modelling," AI-augmented ABM" incorporates adaptive, data-driven, and learning capabilities, such as machine learning algorithms, neural networks, and evolutionary algorithms into ABM (Sánchez et al., 2022). AI-augmented ABM can therefore be beneficial in simulating complex systems and offering insights for agricultural planning and policy. That said, Sánchez et al., 2022 also notes that while AI-augmented ABMs are on the rise, there remains a lack of standardization and validation of methods utilized in the literature.

System Dynamic (SD) modelling and Positive Mathematical Programming (PMP) are also noted as relevant methods for simulating the impacts of different policy scenarios on agricultural technology adoption and sustainability outcomes. A study by Varia et al. (2017) utilized SD modelling to assess the adoption of conservation agriculture practices in Italy under different European Union (EU) agri-environmental supports and incentives. Similarly, Layani et al. (2023) integrated SD modelling with PMP to simulate the impacts of shifting policy regimes and government reform on long-term resource and land-use changes in Iran. Both studies simulate the longer-term impacts of policy scenarios on environmental impacts and sustainability outcomes (Varia et al., 2017; Layani et al., 2023).

Modelling Inputs and Outputs: Behavioural, Environmental, Economic and Policy

Across the reviewed studies, sustainability and technology adoption are examined through four key categories of modelling inputs, including: behavioral factors, environmental factors, economic factors, and policy factors. Modelling inputs are analyzed to generate modelling outputs, including adoption rates, environmental impacts, sustainability outcomes, and system-level transitions. Depending on the study, some factors (e.g., economic or environmental) may be modelling inputs and/or outputs. Many studies integrate modelling inputs and outputs to generate dynamic system-level models that can be utilized to inform agricultural policy and planning.

Behavioural inputs allow for modelling approaches to show how agents respond to policy incentives, risks (e.g., climate change), and social dynamics (Huber et al., 2023; Sun et al., 2022). Huber et al. (2023) show that perceptions of fairness and reluctance to change significantly affect adoption of precision agriculture, while Sun et al. (2022) demonstrate that well-designed extension programs can support earlier adoption of beneficial water management practices. Similarly, a recent NSERC grant awarded to Adamchuk (2023) integrates behavioral science into decision-support tools for understanding farmer's transitions toward sustainable agriculture.

Contributing to system-level modelling, environmental inputs enable researchers to model factors related to natural resources, weather and climate, and assess the impacts of each variable on technology adoption and sustainability outcomes. For example, Coronese et al. (2024) modelled how soil degradation impacts farmer's likelihood to transition from conventional farming practices to sustainable framing practices. Similarly, Sun et al. (2022) utilized GIS modelling and climate data to forecast the "adoption/diffusion of agri-environmental beneficial technology."

In addition to behavioural and environmental inputs, there are **economic and policy inputs**, which are interconnected in the reviewed literature. Examples of economic and policy inputs include financial incentives (e.g., subsidies), investments in infrastructure, and broader policy and regulatory frameworks. Several studies have simulated the impacts of policy scenarios on economic outcomes. For instance, Güldal & Ozcelik (2024) assessed the impact of financial support schemes on smart farming uptake, while Huber et al. (2023) demonstrated that results-based payments may outperform conventional subsidies when behavioural preferences are accounted for. Mack et al. (2023) and Layani et al. (2023) similarly utilized economic inputs, finding that profitability alone does not drive the adoption of agricultural technologies or sustainable agricultural practices, especially under resource constraints. Recently funded research by Hassini (2023) also incorporates socioeconomic concepts such as labour shortages and digital divides into modelling approaches – highlighting the diversity of economic and policy inputs and outputs.

Emerging Sustainable Agriculture Modelling Research in Canada

Two recent (2023) NSERC awards showcase a growing interest in agri-food modelling research in Canada. One NSERC award has been given to Dr. Hassini of McMaster University for the research project entitled '*FARM: A Digital Platform for the Future of Agriculture and Agri-Food Systems*'. Dr. Hassini's research aims to develop an "integrated digital platform" that will model how agri-food systems respond to stressors like climate change, labour shortages, and supply chain disruptions. This research proposes the use of agent-based modelling and system-dynamic modelling to simulate interactions and outcomes related to the adoption of digital technologies and policies, while also exploring implications for social equity and opportunities for industry coordination. The other NSERC award has been given to Dr. Adamchuk of McGill University and is entitled *'Toward a Framework for Modelling Meta-Systems for Farm Decision Support and Policy Design'*. Dr. Adamchuk's research will develop a modelling framework for supporting farm-level decision-making. Building upon behavioural, environmental, and technical data, Dr. Adamchuk plans to develop a "meta-systems" model that would be used to inform both farm management and agri-environmental policy design. Both projects are similar in nature to that of the Just Transitions in Agri-Genomics research team, offering complimentary insights to support agricultural planning and policy across Canada.

Table 3. Relevant research

Title	Date	Authors/Organization	Abstract
Agent-based modeling of policy induced agri-environmental technology adoption	2022	Sun, R., Nolan, J. and Kulshreshtha, S. University of Saskatchewan, Canada	This paper seeks to calibrate the dynamic policy-induced adoption/diffusion of an agri-environmental beneficial technology. The paper develops an agent-based model to integrate the adoption problem into a complex farmer adoption decision-making system involving different components (e.g., GIS environment, agents, network, production and adoption, policy). Based

			on the model, a case on cost-effectiveness evaluation of a hypothetical agricultural extension (AE) program is exemplified in this study to explain how this model can support the agri-environmental policy design. As a result, farmers' adoption decision-making under the influence of the AE program can be brought forward to an average ten-year ahead with a higher upper boundary of ultimate adoption rate than no policy scenario. Furthermore, this study presents simulated policy evaluation from different participation rates of the AE program to compare policy effects and thus assess their cost-effectiveness. The comparison results imply that a higher participation rate does not positively increase the performance of the AE program. Our ex-ante agent-based modeling (ABM) simulation method can be applied in agri-environmental policy design, evaluation, and long-term policy monitor. In addition, the model provides a flexible quantitative tool to predict farmers' policy-induced adoption decision-making and outcomes in a future period. We also introduce potential improvements to extend the inherent farmers' adoption behavior algorithm, computing capability, and model validation for future research.
Bibliometric analysis of publications discussing the use of artificial intelligence technique agent-based models in sustainable agriculture	2022	Sánchez, J. M., Rodriguez, J. P., and Espitia, H. E. Francisco José de Caldas District University, Colombia	The purpose of this article consists of analyzing publications discussing the use of agent-based artificial intelligence models in sustainable agriculture research. The analysis involved bibliometric indicators and the Rstudio software with Bibliometrix library. The methodology is descriptive with a quantitative approach. Scientific databases SCOPUS and Web of Science were consulted and the PRISMA methodology was used during the selection process. This led to finding 86 publications that met the inclusion criteria. Amongst the results, United States was listed as the country with the highest production of scientific material, although France had a higher impact. Additionally, the bibliographical resources that help promote scientific development are open source. It was concluded that the agent-based model has been adopted to simulate different scenarios, which help decision-makers to formulate public policies in favor of sustainable agriculture. This optimizes the use of natural resources and reduces negative consequences for the environment, while also

			delivering value for the stakeholders of the agricultural system.
Towards sustainable agriculture: Behaviours, spatial dynamics and policy in an evolutionary agent-based model	2024	Coronese, M., Occelli, M., Lamperti, F., and Roventini, A. Laboratory of Economics and Management (LEM), Italy	Economic and population growth increasingly pressure the Earth system. Fertile soils are essential to ensure global food security, requiring high-yielding agro-technological regimes to cope with rising soil degradation and macro-nutrients deficiencies, which may be further exacerbated by climate change. In this work, we extend the AgriLOVE land-use agent-based model (Coronese et al., 2023) to investigate trade-offs in the transition between conventional and sustainable farming regimes in a smallholder economy exposed to explicit environmental boundaries. We investigate the ability of the system to favor a sustainable transition when prolonged conventional farming leads to soil depletion. First, we showcase the emergence of three endogenous scenarios of transition and lock-in. Then, we analyze transition dynamics under several behavioral, environmental and policy scenarios. Our results highlights a strong path-dependence of the agricultural sector, with scarce capacity to foster successful transitions to a sustainable regime in absence of external interventions. The role of behavioral changes is limited and we find evidence of negative tipping points induced by mismanagement of grassland and forests. These findings call for policies strongly supporting sustainable agriculture. We test regulatory measures aimed at protecting common environmental goods and public incentives to encourage the search for novel production techniques targeted at closing the sustainable-conventional yield gap. We find that their effectiveness is highly time-dependent, with rapidly closing windows of opportunity.
Behavioural agent-based modelling approach for the ex-ante assessment of policies supporting precision agriculture	2023	Huber, R., Späti, K., and Finger, R. Agricultural Economics and Policy ETH, Switzerland	Precision agriculture technologies can help reduce nitrogen losses and the associated negative environmental impacts. As the adoption rate of such technologies in small-scale farming systems is still low, additional policy measures are required to support their broader application. We provide an ex-ante assessment of policy measures (payments for reduced nitrogen, subsidy for the technology or area subsidies) to incentivize the adoption of sensing technologies for site-specific nitrogen fertilization with a specific focus on farmers' behavioural characteristics such as reluctance to change and

			their individual perception of the policy measures. We combine a bio-economic optimization model with data from a choice experiment, survey, and census data in an agent-based modelling framework. We simulate the impact of the policy measures on farmers' adoption decisions in Swiss wheat production. Simulations suggest that for the same level of nitrogen reduction a results-based payment (paying farmers for reduced nitrogen) is 1.5 times more cost-efficient than area-based subsidies and subsidies for technology use. Our results also suggest that considering how farmers perceive costs and benefits decreases the potential to reduce nitrogen input by ~20%. We conclude that disregarding behavioural factors such as the perception of the instrument may result in a significant overestimation of the policy effect.
Effects of government policies reform on environmental sustainability: An integrated approach of PMP and system dynamics simulation model	2023	Layani, G., Mehrjou, S., and Farajzadeh Z. Shahrekord University, University of Tehran, and Shiraz University, Iran	The government's supportive policies in the agricultural sector may provide some goals intended by policymakers; however, they may have environmental, social, and sometimes economic inefficiencies. Therefore, policy analysis not only needs to examine the effectiveness of these policies from the point of view of economic components but also, in a more comprehensive view, should assess the impact of these policies on other aspects like sustainability. In this study, an integrated Positive Mathematical Programming (PMP) and System Dynamics (SD) model was developed to investigate the effects of the agricultural policy reform on the cultivation pattern and water resources sustainability in the Doroodzan Dam basin in Fars Province, southern Iran, where managing water resources is a seriously challenging due to population growth and periodic drought. The initial investigation involved analyzing how price policies (guaranteed price and world price of crops) and non-price policies (removal of subsidy payments to agricultural inputs and improvement of irrigation efficiency) impacted the cropping pattern. The results of the study showed that the most significant decrease in cropland area occurs due to the removal of agricultural input subsidies. Although this crop pattern can lead to environmental sustainability, it is not considered from the point of view of food self-sufficiency. Based on the results, applying world prices increase cropping area for crops like rice, which is

			a water-intensive crop. Another point was the high priority of onions, fodder corn, and beans while they are not subjected to governmental pricing intervention. This may indicate the extent of public policies' impact on agriculture. Although under some policy scenarios changes in the gross margin or cropping area do not sound significant, the water-saving nature of these policies is more compelling. Finally, the impact of altering cropping patterns along with climate change and population growth on water indices was assessed using SD modeling. Thus, reforming the government's policies in the agricultural sector may help reduce the water shortage index in the basin. The policy of removing subsidies for the agricultural inputs led to the attainment of the lowest water shortage index.
From conventional to smart: Farmer's preferences under alternative policy scenarios	2024	Güldal, H. T., and Özçelik, A. Ankara University, Turkey	This study investigates the impact of ex-ante policy scenarios on conventional farmers' intentions to adopt smart farming applications and identifies influential factors. Through survey data collected from 117 conventional farmers, three scenarios (no support, cash support, credit support) were presented to determine their intention to adopt smart farming. The findings reveal that financial support significantly boosts farmers' intention to adopt these technologies. Additionally, farm income, knowledge, and inheritor positively influence adoption, while education and age hinder it. To promote the adoption of smart farming systems, we recommend providing educational programs to increase farmers' knowledge and offering financial benefits to offset the costs of purchasing and installing the systems. Our findings are relevant for developing countries, such as Türkiye, that are transitioning to smart farming and can inform policies that facilitate the adoption of smart farming systems.
Modelling policies towards pesticide-free agricultural production systems	2023	Mack, G., Finger, R., Ammann, J., and El Benni, N. Agroscope Research Group and Agriculture Economics and Policy Group, Switzerland	CONTEXT: The use of pesticides implies negative effects on human health and the environment. Thus, the reduction in pesticide risks without harming food security and farmers' income is a key policy goal. OBJECTIVE: The aim is to investigate the implications of policies that explicitly foster the large-scale adoption of pesticide-free, non-organic production systems at the national scale

			using Swiss crop production as an illustrative example. METHODS: We develop a bio-economic modelling approach that combines agent-based modelling, a Delphi study to assess yield implications and a detailed representation of labour and machinery implications of pesticide-free, non-organic production. Using an agent-based modelling framework allows the consideration of heterogeneous farm-specific adaptation responses to voluntary direct payments for crop-specific conversion to pesticide-free but non-organic production systems. The modelling framework is used to assess the effects of changing pesticide policies on farm and sector levels and its implications for (crop-specific) food production in terms of area, volume, value and income. Our approach is illustrated using Switzerland as an example, where voluntary direct payments for a crop-specific conversion to pesticide-free but non-organic production systems will be implemented. RESULTS AND CONCLUSIONS: The results show that the extent of crop-specific yield losses has an especially significant effect on the adoption rate of pesticide-free cropping systems. The impacts of introducing voluntary direct payments for pesticide-free production at the national scale imply reduced food (volume) and calorie production but only minimal reductions in the production value, especially due to expected higher prices for pesticide-free products. The effects on farmers' income are small, as participation in pesticide-free production is compensated with direct payments and higher prices and often implies cost reduction in labour and machinery due to non-use of pesticides. To establish large-scale production systems between conventional and organic cropping systems and, thereby, reduce trade-offs resulting from both extremes, policy schemes need to be flexible, allowing the adoption of a pesticide-free paradigm for some parts of the crop rotation but not necessarily entire crop rotations. SIGNIFICANCE: This is the first national-scale study on the implications of adopting a pesticide-

			free, non-organic crop production system by using Swiss crop production as an illustrative example.
System Dynamics Model to Design Effective Policy Strategies Aiming at Fostering the Adoption of Conservation Agriculture Practices in Sicily	2017	Varia, F., Guccione, G. D., Macaluso, D., and Marandola, D. Council for Agricultural Research and Analysis of Agricultural Economics (CREA-PB), Italy	This paper presents a study based on System Dynamics Approach (SDA) whose aim is to support policy and decision makers to design effective policy strategies to foster the adoption of conservation agriculture practices in Sicily. The SDA is a methodological tool that can be used to study and manage complex and dynamic systems characterized by feedback mechanisms, which can be relevantly influenced by the policy & decision-making process and its delays. The SDA may help to define, implement and evaluate decision makers choices from the output of systems to stimulations from the outside. Scientific literature provides important experiences in the field of these simulation models, both for the development of ecological agriculture and for the simulation of the impacts of policy scenarios in a certain region/area. Conservation Agriculture (CA) is a farming system, mainly for arable crops, which helps to achieve goals of sustainable and profitable agriculture. It is currently playing an ever-increasing role in the frame of EU agricultural policies in consideration of the positive impacts it can produce, in terms of sustainable use of natural resources as well as of Climate Change mitigation and adaptation. At farm level, moreover, CA represents a way to combine environmental and sustainability concerns with profitability and competitiveness aspects, in a variety of agroecological zones and farming conditions. Short-term solutions and immediate benefits always attract farmers more than long-term ones. Unfortunately, the full technical, environmental and economic advantages provided by the adoption of CA can be measured and appreciated by farmers only in the medium and long-term, when its principles (minimum soil disturbance, permanent soil cover crop rotation) are well established within the farming system. This evidence, together with other technical, social and cultural forces, relevantly affects the process of CA adoption at farm level as well as the effectiveness of agricultural policy efforts aiming at this result. The aim of this study is to validate a Systemic Dynamic Model (SDM) to be used in ex-ante evaluation to address the public

			action towards the effective achievement of the planned result of supporting the adoption of CA techniques in a certain region. It seeks answers to strategic questions related to the elements that could influence the effectiveness of the support payment schemes programmed into the sub-measure 10.1 of 2014-2020 Sicily Rural Development Programme (SRDP). The SDA considers relevant variables which affect the application and dissemination of CA techniques among potential beneficiaries whose number is estimated based on sub-measure access conditions and restrictions. For this purpose, the model structure is based on environmental, social and economic issues, e.g. physical and economic farm dimensions, provision of machinery hire, advisory services, reduction of production costs, etc. Results show that in a long term dynamic context the environmental support payment scheme provided by Measure 10 does not represent the only driving force in the system to guide farmers towards the expected shift from conventional to CA agriculture. What is needed is a deeper integration with other policies (innovation policies) and other interventions, e.g. schemes promoting precision farming, collective investments, advice, training and information.
A meta systems approach to assure sustainability of Canadian farm operations	2023 (Project Began)	Adamchuk, V. McGill University, Canada	NSERC Grant Description: It is essential that the Canadian agricultural sector makes significant efforts to maximize its financial viability, reduce air, soil, and water pollution, and adapt to climate change. To achieve a more sustainable agriculture, producers need to integrate new practices. However, adoption of new practices has been an ongoing challenge due to lack of certainty of long-term benefits. Multiple risks combined with the lack of clear roadmaps when adopting new digital technologies and other best management practices have been major limiting factors. This project proposes a new and unique meta systems approach to equip the Canadian agricultural sector with the necessary tools to make informed decisions when comparing alternative macro management and micromanagement scenarios. This will eliminate both the technical and behavioral obstacles which prevent producers from realizing the potential benefits accrued from the successful adoption of new technologies and the optimization of their farming practices. The technical stream will

			encapsulate a holistic simulation framework that will integrate different layers of contemporary and new information to improve production systems. The framework will be applied to several production agriculture scenarios common to the Canadian farming landscape. The behavioral stream will identify social limitations and seek an improved communication infrastructure to assist agriculture practitioners to develop pragmatic pathways to enhance the sustainability of their production systems. Through harmonization of agricultural data analytics and behavior science, this project aims to maximize the adoption of viable alternatives to traditional farm management to ensure the highest probability of improved production sustainability.
Farming Analytics and Resilience Modelling (FARM)	2023 (Project Began)	Hassini, E. E. McMaster University, Canada	NSERC Grant Description: Farming is an essential component of the Canadian economy and plays a significant role in achieving a sustainable future. Economically, it contributed $71.7 billion to Canada's GDP in 2019, employs over 2.3 million people and contributed to more than 17% of Canada's experts. Socially, farming is a vital source of income for many rural communities in Canada and serves as support line for other businesses and services. Environmentally, farming play a critical role in managing natural resources, reducing greenhouse gas emissions and so help in mitigating climate change and preserve natural ecosystems. Despite its importance, farming is facing multiple challenges. The purpose of this research is to develop collaborative solutions to address the following challenges: (1) Climate change: Farmers are increasingly facing unpredictable weather patterns and extreme weather events, which can damage crops and livestock, resulting in highly uncertain yields. Coupled with pests and diseases outbreaks, the disruptions brought by the COVID pandemic and global political instability, farmers have to deal with highly uncertain demand swings; (2) Labour shortages: Farmers in Canada rely heavily on temporary foreign workers to fill labour shortages. In addition, farmers are aging with no clear succession plans, that threaten the sustainability of food supplies; (3) Digitalization of the food supply chain: While technology adoption and digitalization in the food supply chain can offer significant benefits there are several

			challenges that need to be addressed to ensure successful implementation. In this research we focus on (3-a) data management, including security and privacy, (3-b) workforce training and (3-c) access to reliable internet and technology infrastructure; and (4) Delivery of veterinarian services in remote areas where we investigate the various barriers to accessing affordable healthcare for livestock in remote areas and the application of innovative solutions (telemedicine, drones and e-commerce approaches) to ensure equitable animal healthcare in remote regions of Canada. This research will provide technology solutions and policy to improve equitable and sustainable access to a resilient food ecosystem for Canadians.

Global Patent Analysis

The global patent review is a high-level summary of patent activity based on simple patent families[20]. Reviewing patenting activity offers critical insights on the competitive landscape and market position over the medium term and identifies potential barriers to development, commercialization, acceptance and adoption.[21] The patents listed in Table 4 are representative, rather than exhaustive, examples of relevant global patents that address the same challenge or solve the same problem.

A search of Espacenet for simple patent families was performed. An initial search was done for relevant modelling tools, without adding key words related to agriculture, policy, sustainability, or technology. This broad search yielded 1665 results, with patents spanning 1974-2025 – most of which have been published within the past 20 years (2005-2025). Next, a more tailored search was performed, which combined terms related to technical and mathematical modelling approaches with relevant key words related to policy, sustainability, and technology, and ensured that agriculture was a potential application of the patent. The tailored search resulted in 403 results, spanning from 1997 to 2025. Most of these results (~98%) were patent families published within the past 20 years. Temporal trends in patenting activity also highlight an uptick in relevant patents beginning in the early 2010s (Figure 1). The highest level of patenting activity was in 2024, indicating a growing level of global research and development related to agricultural modelling tools.

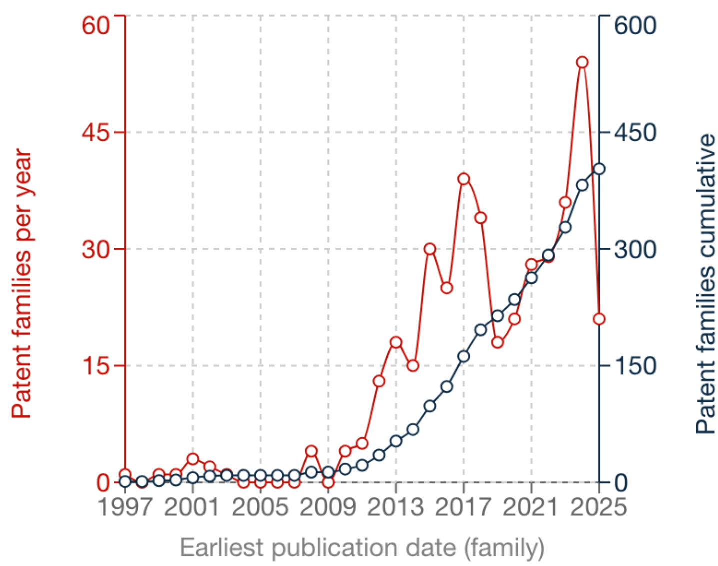

Figure 1. Temporal overview of patenting activity for 403 global patent families on modelling tools or simulation approaches related to agriculture, environmental sustainability, technology adoption, and/or policy scenarios. Dating trends are based on the earliest publication date for each patent family. Figure generated through Espacenet.

[20] A simple patent family is a group of patents that describe a single invention. They cover the same or similar technical content. For example, patents in various jurisdictions for the same invention belong to a simple patent family.
[21] The global patent analysis does not to provide a legal determination of 'patentability' or freedom-to-operate.

The country with the highest number of agricultural modelling patents is China. This is followed by patents filed in the United States (USA) and Europe. Of the 403 relevant patent families identified, only 3 patent families had patents filed in Canada. These patents do not have Canadian applicants or inventors. Instead, inventors come from different countries, including China and the USA. Moreover, the patents filed in Canada (CA2895245A1, CA2406907C, CA3029179C) are slightly older in their publication dates (2010, 2012, and 2015), and are less relevant to the work being performed by the Just Transitions in Agri-Genomics research team. For example, CA2895245A1 describes a dynamic simulation that can support planning for municipalities and institutions, but is less relevant to agriculture. Meanwhile, China and the USA have filed patents that more adequately reflect the research goals of the Just Transitions in Agri-Genomics research team.

Most of the global patents come from research institutions and universities, indicating that this field of research and development is being initiated primarily by academics. A smaller number of patents have been filed by private companies, including ag-tech startups in the USA. The leading private corporation patenting in this field is CIBO Technologies Inc., a USA-based company focused on creating and delivering technology solutions that "enable companies to forecast, model, monitor, verify, and report (MVR) regenerative farming practices across portfolios of land and supply chains."[22] Another private patent holder is Inari Agriculture Tech, a USA-based company led by the same founder as CIBO Technologies, suggesting that there may be overlap in research and development capacity or activities between the two companies.[23]

Through a thematic analysis of relevant patents, three key themes emerged. The first theme relates to common simulations in the patenting literature, covering the topics of climate change, greenhouse gas emissions and policy scenarios in the context of agricultural systems modelling. The second theme relates to technical advances in the patenting literature, touching on novel approaches to modelling agricultural systems. The third and final theme discusses the multi-dimensional nature of patents in the field of agricultural systems modelling and the interactive platforms and web tools used to present such simulations.

Common Simulations: Climate, Greenhouse Gases, and Policy Scenarios

Modelling variables outlined in the patent literature include climate change, greenhouse gas emissions, and policy scenarios. Modelling related to climate change scenarios and greenhouse gas (GHG) emissions were more common, while patents related to modelling the impacts of policy scenarios in agriculture were less common. Most of the patents are developed by Chinese inventors and have the most applicability to the Chinese agricultural landscape. Moreover, many relevant patents modelling climate change, greenhouse gases, and policy scenarios on agricultural systems are recent applications, published within the past ~ five years, highlighting the recency of this field of technology development.

There is an emergence of patents that include climate change and greenhouse gas emissions (e.g., CO_2) as core variables in agricultural system modelling. Some of these patents simulate the

[22] https://www.cibotechnologies.com/about/
[23] https://inari.com/about-us/

impacts of different management practices on sustainability outcomes such as GHG emissions mitigation. For example, CN118504994A describes an approach for simulating soil carbon storage under different farming practices. This patent incorporates meteorological data, crop growth information, and land-use data to simulate sustainability outcomes (carbon sequestration) and inform farming practices. Similarly, a recent patent application (CN119671707A) describes a method for simulating variables such as fertilizer type, tillage frequency, and crop rotation schedules to simulate changes in soil carbon fluxes and resulting GHG emissions. A US-based patent (US11763271B2) similarly simulates the impacts of greenhouse gas emissions under different regenerative agriculture practices. Meanwhile, GB2626437A describes an approach to simulating agricultural field capacity (plot-scale paddy field production) under different climate scenarios. This patent incorporates multiple layers of data and modelling approaches, including geospatial data and a Decision Support System for Agrotechnology Transfer (DSSAT) model.

Compared to patents related to climate change, patents that simulate policy scenarios are less common. One of the most relevant patents to the research of the Just Transitions in Agri-Genomics research is CN118052134A, entitled ‘Policy regulation and control simulation method and system for agricultural planting behaviours. This patent utilizes agricultural data and policy data to simulate the impacts of policy scenarios on farmer’s behavioural responses, including whether farmers would switch crops under varied scenarios. Another Chinese patent application, CN114676590A, presents a decision simulation model that incorporates numerous “modules” including behavioural and government modules. This patent offers a policy simulation engine that allows users to adjust variables like subsidy amounts to identify behavioural, economic, and environmental impacts in the context of agricultural systems.

Several patents focus on simulating the impacts of different agricultural practices on sustainability outcomes (e.g., CN118504994A, CN119671707A, US11763271B2). However, no patents were found that focus on simulating the impacts of technology adoption on sustainability outcomes, or the impacts of policy scenarios on technology adoption in the agriculture sector specifically. Moreover, most patents that discuss modelling policy scenarios are relatively new and relate predominately to policy scenarios relevant to the Chinese agricultural system (e.g., CN118052134A, CN114676590A).

Technical Advances: Artificial Intelligence, Machine Learning, and Digital Twins

An emerging trend in recent patents and patent applications is the integration of artificial intelligence (AI), machine learning (ML), and digital twin technologies into modelling and simulation approaches. Some patents directly label the invention as including AI and/or ML, while others embed the principles of AI and ML into their invention description using different labels, like “decision engines.” This is the case for a recent patent application filed in the USA (US2025021722A1). This patent presents a decision engine that can support agricultural land-use planning under different environmental or market-based constraints or scenarios (US2025021722A1). Similarly, CN119150593A outlines an approach to behavioural modelling that may utilize ML algorithms trained on observed behavourial data, ultimately enabling for farmer’s responses under different policy and market scenarios to be modelled.

One patent application (CN119671707A) introduces a novel approach that involves "causal artificial intelligence (Causal AI)" paired with digital twin simulations. The patent application details a methodology for developing a "structural causal model" that uncovers the relationships between agricultural variables, such as climate data, pests, crop yields, and policy interventions, and the impacts of these variables on credit risks. The digital twin component of this patent application allows for the simulations to be presented in a virtual agricultural environment. This patent is novel in that it integrates AI with digital twin technologies. Other patents also note the creation of digital twin technologies for modelling agricultural systems. For example, CN119671707A presents a modelling approach that utilizes real-time sensor data in the digital twin model.

Multi-Dimensional Simulation Platforms and Tools

A common trend across the patent literature is the integration of different variables to model agricultural system dynamics. As opposed to treating data (e.g., biophysical, behavioural, policy, economic) as static variables, patents tend to integrate variables through system and dynamic modelling approaches (e.g., US2025021722A1). Depending on the patent, the multi-dimensional simulation may have a different name. For instance, CN118052134A presents a "multi-model simulation system," CN114676590A presents a "composite decision system," and US2025021722A1 presents a "land allocation decision system." All of these patents are multi-dimensional in nature.

Some patents also describe the development of integrated platforms and tools that enable flexible scenario testing across multiple agricultural dimensions. For example, CN118052134A presents a simulation platform that includes visualization dashboards, policy modules and behavioural data. This platform can be used by stakeholders to evaluate policy and sustainability outcomes on agricultural systems. Similarly, US2025021722A1 offers a methodology for building a "geospatial decision-support system" platform designed to support policy decision making as well as farm-level decisions. Both patent applications are new (2024 and 2025 respectively), highlighting the recency of multi-dimensional modelling platforms and tools patented for agricultural systems.

Table 4. Relevant patents and patent applications

Title	Patent Publication #/Year	Applicant/Assignee	Abstract
Predictive Agricultural System and Dynamic Modelling Tool	US2025021722A1 2023	Applicant: Inari Agriculture Tech Inc. (USA) Inventors: Anya Gandy, Nicole Neville, Howard Buffet (USA)	A system is used to perform systems modeling related to at least agriculture. The system can include a memory unit that stores executable instructions wherein the instructions can be used to perform systems modeling. The system can obtain, store, and use historical data related to agricultural scenarios. The system can further generate and/or display a human machine interface wherein a user can enter input to tailor the input data based on the preferences and/or assumptions of the user. The

			system is further configured to perform a simulation based on the user-defined input data. The system can then provide and/or display the results of the simulation as output data The output data can include predicted and/or projected outcomes based on the input data wherein said outcomes can include agricultural information, market information, environmental information, and/or farm management information. The disclosure allows for accurate modeling of complex systems.
Policy regulation and control simulation method and system for agricultural planting behaviours	CN118052134A 2024	Applicant: Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (China) Inventors: Zhihui Li, Haowei Wu, Feng Wu, Xing Gao, Xianhua Wu, Ng Guangji Bao (China)	The invention discloses a policy regulation and control simulation method and system for agricultural planting behaviors, and the method comprises the steps: obtaining various agricultural data and policy information related to agriculture; constructing a simulation model; the simulation model is operated, influences of different policies and measures on farmer planting behaviors, agricultural production, market demands, earnings and the environment are simulated, and simulation results are output; and performing clustering analysis on simulation results, predicting the influence of different policy measures on the development of agriculture and the income of farmers according to the simulation results, and giving scientific policy making suggestions. According to the method, a computer simulation technology is used, various agricultural data and policy information are combined, the influence of different policy measures on agricultural production, earnings and the environment is predicted by simulating planting behaviors and policy influences of farmers, and scientific basis and data support are provided for policy making.
Accessing agricultural productivity and sustainability	US20220611236A1 2020	Applicant: University of Illinois, USA Inventors: Kaiyu Guan, Bin Peng, Chongya Jiang, Wang	An integrated multi-scale modeling platform is utilized to assess agricultural productivity and sustainability. The model is used to assess the environmental impacts of agricultural management from individual fields to

		Zhou, Jingwen Zhang, Yizhi Huang, Jian Peng, Sibo Wang (USA)	watershed/basin to continental scales. In addition, an integrated irrigation system is developed using data and a machine-learning model that includes weather forecast and soil moisture simulation to determine an irrigation amount for farmers. Next, crop cover classification prediction can be established for an ongoing growing system using a machine learning or statistical model to predict the planted crop type in an area. Finally, a method of predicting key phenology dates of crops for individual field parcels, farms, or parts of a field parcel, in a growing season, can be established.
Plot-scale paddy field production capacity simulation method	GB2626437A	Applicant: Nanjing Agricultural University (China) Inventors: Penghui Jiang, Haiyue Fu, Manchu Li (China)	A plot-scale paddy field production capacity simulation method comprises: obtaining data source information; pre-processing the data source information to obtain pre-processed data; performing a land use change simulation based on the pre-processed data; analyzing climate change; and simulating arable land production capacity. Pre-processing the data source information comprises: ANUSPLIN model data processing; Decision Support System for Agrotechnology Transfer (DSSAT) model data 10 processing, involving the use of ArcGIS; and agricultural data pre-processing. A CERES cereal model simulates the growth, development, and yield changes of rice.
Water resource management simulation method based on multiple subjects	CN119150593A 2024	Applicant: University of Beijing Normal (China) Inventor: Song Shuang (China)	The invention relates to the technical field of water resource management, in particular to a water resource management simulation method based on multiple subjects. The method comprises the following steps: acquiring different data sources corresponding to a river basin; a water resource management model is constructed, a water resource management main body, a plurality of agricultural irrigation main bodies, a natural sub-model and a social sub-model are created in the water resource management model, social connection among the plurality of

			agricultural irrigation main bodies is established, and the social sub-model is used for providing a public pond game framework; the water resource management model acquires a data source, the natural sub-model estimates and outputs the crop water demand under the driving of meteorological data, and the agricultural irrigation subject simulates and outputs an irrigation water decision under a public pond game framework based on historical water resource survey data, the crop water demand and a water resource management decision. And the water resource management main body simulates water resource management decisions and influences thereof under a public pond game framework. According to the method, the agricultural irrigation water decision-making process can be described more accurately, and the influence of water resource management can be simulated more practically.
Method and system for carbon footprint determination based on regenerative practice implementation	US11763271B2 2020	Applicant: Cibo Tech Inc. (USA) Inventor: Jenette M. Ashteka, Pankaj C. Bhambh, Ernesto Breau, Marie A. Coffin, Margare T. C. Kosmala (USA)	A system for determining regenerative carbon footprint in agricultural parcels, including: a sequestration server, having: a management processor that builds first simulation inputs that correspond to baseline management practices, and that builds second simulation inputs that correspond to regenerative management practices; a crop simulation processor, that employs the first simulation inputs to simulate crop growth for a prescribed number of growing seasons to generate first outputs, and configured to employ the second simulation inputs to simulate crop growth for the prescribed number of growing seasons to generate second outputs; and a CO2E determination processor, that employs the first outputs and the second outputs to compute baseline annual carbon dioxide emissions and regenerative annual carbon dioxide emissions, and configured to subtract the baseline annual carbon dioxide emissions from

			the regenerative annual carbon dioxide emissions to yield a regenerative carbon footprint for the first agricultural parcel.
Assistant decision making system for agricultural planting	CN103886409A 2014	Applicant: University of Shantou Inventor: Zhuang Lihong	The embodiment of the invention discloses an assistant decision making system for agricultural planting. The assistant decision making system for agricultural planting comprises a data processing and decision making system and a display terminal. The data processing and decision making system combines environment data with geographic data of a region and conducts evaluation and calculation. The display terminal classifies and displays evaluation and calculation results of the data processing and decision making system. According to the auxiliary decision making system for agricultural planting, an adopted information platform can integrate a plurality of heterogeneity databases, such as a farming, climate and soil database, and the adopted information platform, the geographic information system and the general circulation model are integrated into a global climate variation decision support system; simulation and analysis are conducted by means of calculation of a cloud platform, and for the topics such as the greenhouse effect, water source management, farmland resource sustainable utilization, agricultural insurance essential data and agricultural disaster loss evaluation, decision-making is assisted.
Credit strategy determination method and device, program product and storage medium	CN119671707A 2024	Applicant: Agricultural Bank of China (China) Inventor: Zhao Jing	The embodiment of the invention discloses a credit strategy determination method and device, a program product and a storage medium. The method comprises the following steps: performing causal analysis on agricultural production data by using a causal artificial intelligence technology to obtain a causal analysis result; simulating an agricultural production process corresponding to the agricultural production data by using a digital twin technology to obtain a

			simulation result; and determining a target credit strategy based on the causal analysis result and the simulation result. Therefore, the causal artificial intelligence technology and the digital twinborn technology are combined, the causal relationship in agricultural production can be deeply analyzed, and the change of the agricultural production environment can be reflected in real time, so that more accurate and dynamic support can be provided for credit decision, and an adaptive credit strategy can be provided for an agricultural production unit.
Simulation model for individual decision	CN114676590A 2022	Applicant: Agricultural University in China (China) Inventor: Hang Xiong (China)	The invention relates to the technical field of individual decision simulation models, in particular to an individual decision simulation model, which adopts modular programming and comprises a behavior module, an individual module, a government module, a decision module, a main function module, a file management module and an interface module. A mathematical programming method is used as an algorithm basis, decision-making behaviors of effectiveness maximization or profit maximization of a behavior main body are simulated under resource constraint conditions, the application field of the model is widened, and a built-in algorithm is suitable for solving decision-making problems in the fields of agriculture, industry and the like. And the value of the existing data can be utilized to the maximum to assist individual decision making.
Economic risk prediction method, system and equipment based on heat wave and flood composite disaster	CN118504994A 2024	Applicant: University of Wuhan Yin Jiabo (China) Inventors: Xihui Gu, Minglong G. Dai	The invention provides an economic risk prediction method, system and device based on heat wave and flood composite disasters, and the method comprises the steps: collecting a meteorological hydrological social economic data set, and calibrating a plurality of machine learning models; training a machine learning model by adopting the corrected global climate mode set meteorological simulation data to obtain a daily runoff process in

			a future scene; combining the global climate mode set with a machine learning model, and determining each combination scene weight parameter in a multi-model weighted average method; extracting a wet bulb temperature and a pathogenic high temperature stress index based on the reanalysis data, establishing a disease-high temperature regression model in the flood season, and solving model parameters; and predicting population, GDP and agricultural risks caused by future composite disasters based on weight parameters of each combination scene in the multi-model weighted average method, and calculating comprehensive social economic risks. According to the invention, an important reference basis with high operability is provided for risk assessment and early warning of extreme climate disasters.

Market Positioning

Commercial Solutions

Reviewing commercial solutions (products, processes and services) identifies current technological capabilities and provides information on current stakeholder needs and benchmarks for performance. Table 5 includes relevant commercially available—or soon to be launched—products, services or processes in the global marketplace that could compete with agricultural modelling tools developed by the Just Transitions in Agri-Genomics team in the short-term.

A Google search was conducted to identify commercially available modelling tools that support sustainable agriculture decision-making, both from a policy perspective and from a farming perspective. This search revealed that most of the relevant agricultural modelling tools have been developed by or funded by government agencies, inter-governmental agencies, and/or non-profit organizations. Tools developed by these agencies and organizations are typically free, publicly available, and aimed to support data-driven decision making for agricultural systems at national and international scales. Fewer agricultural modelling tools have been developed as commercial products by private companies.

The leading group offering agricultural modelling tools is the Food and Agriculture Organization (FAO) of the United Nations (UN).[24] The FAO has developed over twenty software models that can be downloaded and used for free to assist policy decisions, research projects, and field decisions.[25] Key databases and software models enable a deeper understanding of soil health, crop-water productivity, global water information, and the impacts of climate change and policy decisions on socio-ecological and economic aspects of agriculture.[26] Two notable modelling programs by the FAO include the Modelling System for Agricultural Impacts of Climate Change (MOSAICC), and the Adaptation, Biodiversity, and Carbon Mapping Tool (ABC-Map) (Table 5). MOSAICC offers insights into agricultural sustainability (environmental, social, and economic) under a changing climate, while ABC-Map offers insights into the environmental impacts of national policies, plans and investments in natural resources sectors, including agriculture.

In addition to the UN, other research institutes and non-profits are also offering free modelling tools. One leader in the development of these tools is the Consultative Group on International Agricultural Research (CGIAR), which includes several international research partners.[27] CGIAR's Climate Smart Modeling and Futures Initiative has been active for more than 35 years, and works to "inform crucial policy on agriculture, development and climate adaptation around the world."[28] This initiative has led to the development of the International Model for Policy Analysis (IMPACT), which examines the impacts of agricultural policies and practices on sustainability outcomes, including GHG emissions, food security, biodiversity, water quality, prices and trade, crop yield,

[24] https://www.fao.org/home/en/
[25] https://www.fao.org/land-water/databases-and-software/en/
[26] https://www.fao.org/land-water/databases-and-software/climwat-for-cropwat/en/
[27] https://www.cgiar.org/
[28] https://www.cgiar.org/innovations/climate-smart-modeling/

and more. Moreover, a non-profit organization called En-Roads offers a free decision support tool that can help sustainability leaders, policy makers, and researchers assess the impacts of programs and policies (e.g., GHG emissions reductions targets in specific industries, including agriculture) on global climate change.[29] En-Roads offers free training to teach individuals how to utilize the tool to support decision making processes.

Very few agricultural system modelling tools have been developed and sold by private companies. When searching for commercial solutions, i-Open Group's Agrilyze's platform was one of the first search results, highlighting the company as a leader in agri-food modelling in Canada, and underscoring their value as a commercialization partner.[30] Another ag-tech company leading in agricultural modelling is CIBO Technologies, based in the USA.[31] CIBO offers a modelling tool that measures and simulates carbon intensity and carbon sequestration of agricultural land under sustainable practices, such as regenerative agriculture. The tool is marketed as being beneficial for managing and tracking the impacts of sustainable agricultural programs on GHG emissions reductions.[32] CIBO technologies have patented their technology (see Table 4). Furthermore, an Australian ag-tech startup called Agronomeyre is offering digital twin simulation technologies for the agriculture sector, which track and simulate above and below ground biophysical data, serving as a decision-support tool for farmers.[33] This digital twin solution echoes trends in the patent literature, whereby an increasing number of agricultural digital twin methodologies and platforms are being patented. Unfortunately, none of these companies offered pricing data. Demos can be requested, and pricing is likely customized based on individual client needs.

No commercially available modeling tools or interactive platforms were found that simulate the impacts of policy scenarios on the adoption of agricultural technologies, signaling a potential gap in the market.

Table 5. Relevant commercial solutions

Name of Product, Process, Service	Company	Description
Modelling System for Agricultural Impacts of Climate Change (MOSAICC)	Food and Agriculture Organization (FAO) of the United Nations	MOSAICC is developed by the United Nations FAO within the framework of the European Union and FAO "Improved Global Governance for Hunger Reduction" programme. The modelling system integrates five key components: climate, crops, hydrology, forests, and economy.[34] The tool provides a better understanding of agricultural sustainability (environmental, social, and economic) under a changing climate.

29 https://www.climateinteractive.org/
30 https://www.i-opentech.com/products/agrilyze/
31 https://www.cibotechnologies.com/
32 https://www.cibotechnologies.com/platform
33 https://agronomeye.com.au/
34 https://www.fao.org/in-action/mosaicc/models/en/

		The modelling system has been developed to be transferred to interested countries, with training towards independent use by national experts.[35] End-users include researchers and students in the fields of agronomy, hydrology, forestry, and economics. The model is designed to support "least developed nations" and has been applied in Morocco, The Philippines, Peru, Indonesia, and Uruguay.[36] MOSAICC is based on the open-source Linux distribution called CentOS, a web-based interface that is "user friendly" and publicly available.[37] The modelling tool is free.
The Adaptation, Biodiversity, and Carbon Mapping Tool (ABC-Map)	Food and Agriculture Organization (FAO) of the United Nations	The ABC-Map is a geospatial app based on Google Earth Engine that assesses the environmental impact of national policies and plans and investments in agriculture, forestry, and other sectors. End-users of the tool include policymakers and project designers that can leverage modelling data to assess the impacts of policies and programs on sustainability outcomes (e.g., biodiversity, greenhouse gas emissions)[38] Like all modelling tools from the FAO, the ABC-Map is a free tool.[39]

35 https://openknowledge.fao.org/server/api/core/bitstreams/ae4eeec2-2835-41d2-ae74-511392e958bf/content
36 https://www.fao.org/in-action/mosaicc/en/
37 https://www.fao.org/in-action/mosaicc/capacity-development/platform/en/
38 https://data.apps.fao.org/catalog/dataset/abc-map
39 https://www.fao.org/land-water/databases-and-software/en/

Climate Smart Modeling and Futures Initiative has worked to develop global modelling tools such as the International Model for Policy Analysis (IMPACT) model.	Developed by the Consultative Group on International Agricultural Research (CGIAR), with numerous international research partners, including the Alliance of Biodiversity International & The International Food Policy Research Institute (IRFPI) based in Washington, DC.	The Climate Smart Modelling and Futures initiative has led to the development of modelling tools that "support analysis of food and agricultural policies, and to conduct foresight analysis." The IMPACT model examines biophysical and economic outcomes under several scenarios, including climate futures, population growth, income growth, demand parameters, and study parameters. Primary outputs are supply/demand, yields/production, prices and trade, food security and nutrition, GHG emissions, biodiversity, water quality, and welfare analysis.[40] The model is free and includes a publicly available interactive platform that can be modified to examine specific regions, crop types, supply and demand, herd size, prices, food security, and more. The Climate Smart Modelling and Futures initiative has led to the development of other agri-food system modelling tools, some of which are global in scale while others are developed for a specific region.[41]
CIBO Modelling Platform	CIBO Technologies USA ag-tech company with founders from the Massachusetts Institute of Technology (MIT)	Offers a modelling tool and platform that measures carbon intensity and carbon sequestration of agricultural land under sustainable practices, such as regenerative agriculture. The platform is designed to measure the impacts of sustainability initiatives, including financial incentive programs and capital investments on sustainability outcomes. The modelling platform is designed for non-profits, government, sustainability consultants, and industry. Targeted industries include agribusiness, food and beverage, and biofuels. There is no cost data available for the platform. A demo can be requested from their sales team to learn more.
Agronomeyre's AgTwin	Agronomeyre, an Australian ag-tech startup with support from Microsoft and The Commonwealth Scientific and Industrial Research Organisation (CSIRO) of the	The AgTwin platform uses Lidar technologies to map agricultural properties, enabling for the creating of an agricultural digital twin.[42] The AgTwin includes a dynamic map of above and below ground biophysical components and enables farmers to plan farming decision using the tool. There is no pricing data available. A demo can be requested from their sales team to learn more.

[40] https://www.ifpri.org/project/ifpri-impact-model/
[41] https://www.cgiar.org/innovations/climate-smart-modeling/
[42] https://agronomeye.com.au/

	Australian Government	
En-Roads Climate Solutions	Offered by Climate Interactive, and developed by MIT Sloan and Vantana Systems	"En-ROADS is an online simulator that provides policymakers, educators, businesses, the media, and the public with the ability to test and explore cross-sector climate solutions."[43] While not directly linked to agriculture, it is a decision support tool that can help leaders and policy makers assess the impacts of programs or policies (e.g., GHG emissions reductions goals in specific industries, including agriculture) on global climate change. The End-ROADS tool is free to use, and can be accessed here. Climate Interactive offers free training on climate leadership, including how to use the En-ROADS simulation tool to inform decisions around sustainability policies and programs.

[43] https://www.climateinteractive.org/en-roads/

Niche Overview

A potential niche, which is an alignment between a market and an application for an innovation, is discussed in Table 6. The niche profile examines the fit between the innovation and the pre-determined niche. It looks at growth trends, market size, barriers to entry and key drivers. Market trends are global.

Agricultural system modelling/simulation tools and decision support systems do not fall under a single traditional market. Instead, they overlap with several broader markets. Relevant markets that include agriculture as an applicable segment or end-use include the following:

- Simulation Software Market[44]
- Decision Support System Market[45]
- Digital Twin Market[46]
- 3D Mapping and Modelling Market[47]

Of these markets, the decision support system (DSS) and software simulation markets are the most aligned with the innovative tool(s) being developed by the Just Transitions in Agri-Genomics research team. A report by Grand View Research states that DSS in agriculture is growing as a common tool utilized by farmers to support crop management and planning.[48] While DSS and software simulation are most aligned with the modelling tools being developed, there are other substitutable alternatives on the market that can accomplish similar outcomes (e.g., mapping the impacts of policy scenarios on sustainability outcomes in agriculture). Both digital twins and 3D mapping and modelling fall under this category.

DSS, simulation software, digital twins, and 3D mapping and modelling technologies are all experiencing rapid growth (Table 6). The largest markets are simulation software and digital twins, valued at USD 23.56 billion[49] and USD 23.4 billion[50] respectively. The digital twin market is expected to experience the most unprecedented growth, with market research projecting it to grow to USD 219.6 billion in 2033, with a compound annual growth rate (CAGR) of 25.08% between 2025 and 2033.

While the markets discussed in Table 6 cover different technology verticals, they have similar market drivers and barriers. Common market drivers include technological advancements in AI and ML, the adoption of cloud computing technologies, government policies and priorities, and an increased focus on resource efficiency and sustainability across numerous industries. Common market barriers include concerns related to data privacy and cybersecurity, and the upfront cost associated with developing and deploying the software and tools. Two additional market barriers

[44] https://www.marketsandmarkets.com/Market-Reports/simulation-software-market-263646018.html
[45] https://www.fortunebusinessinsights.com/decision-support-system-dss-software-market-104835 ; https://www.grandviewresearch.com/industry-analysis/decision-support-system-market-report#
[46] https://www.researchandmarkets.com/reports/5936063/digital-twin-market?srsltid=AfmBOoqRJZxnAnk3GNXwMotjX8J6DW95XJwHRTPMhY81QCbgqTPB9Zmt&utm
[47] https://www.fnfresearch.com/3d-mapping-and-modeling-market
[48] https://www.grandviewresearch.com/industry-analysis/decision-support-system-market-report
[49] https://www.grandviewresearch.com/industry-analysis/simulation-software-market
[50] https://www.researchandmarkets.com/reports/5936063/digital-twin-market

have been identified specific to the modelling tools being developed by the Just Transitions in Agri-Genomics research team. These include the fact that government agencies and intergovernmental agencies, such as the Food and Agriculture Organization of the UN, are offering free agri-food system modelling tools for "public good" rather than commercial profit. Additionally, the narrow group of end-users (e.g., government, researchers, and agricultural consultants like certified crop advisors) could limit growth potential. Considering market growth, barriers, and drivers, this assessment assigned high market growth potential to software simulation tools, decision support systems, digital twins, and 3D mapping and modelling tools. However, the market potential for these tools and solutions in the agriculture sector is slightly lower. As such, a medium market potential has been assigned to the technology being developed by the Just Transitions in Agri-Genomics research team.

Table 6. Niche Overview for Agricultural System Modelling Tools

Potential	Overview
Medium to High	While this assessment is focused on agricultural system modelling tools that simulate the impacts of different policy scenarios on technology adoption and sustainability outcomes, the niche overview detailed in this table draws upon broader market research. This includes market research on the decision support system (DSS) market and the software simulation market – both of which reflect the innovation being developed by the Just Transitions in Agri-Genomics research team. Market research on the digital twin market and the 3D modelling and mapping – both of which represent substitutable alternatives – are also included. Insights from each market were utilized to understand drivers and barriers to growth of the modelling tools being developed by the Just Transitions in Agri-Genomics research team. The overall potential for the broad markets of simulation software, DSS tools, digital twins, and 3D modelling and mapping tools is high. Each of these markets are experiencing rapid global growth in numerous industries, including health care, aerospace and defense, energy and utilities, and business management. While market potential for these tools is very high, the market potential for each tool in the agricultural sector is medium. Adoption of modelling tools in agriculture could be hindered by challenges related to cybersecurity, upfront cost, the limited number of end-users, and the fact that there are free, open-sourced, agri-food modelling tools already available.

Market Trends	Market Drivers	Market Entry Barriers
The **decision support system (DSS) market** is projected to grow from USD 18.64 billion in 2025 to 52.21 billion by 2034, with a CAGR of 12.12%.[51] The adoption of DSS technologies in agriculture is rising. According to Grand View Research, "DSS has gained prominence in the	**Technological advancements**: Artificial intelligence (AI) and machine learning (ML) are increasingly being integrated into simulation software and modelling tools, improving data processing power and accuracy, and driving market growth. According to Markets and Markets, "AI-driven simulations can analyze vast amounts of data, identify patterns, and make	**Data ownership, privacy and security**: While cloud technologies offer benefits, they also pose security concerns: "as more businesses adopt cloud platforms that operate remotely, the possible data vulnerability due to breaches and cyberattacks has

[51] https://www.marketresearchfuture.com/reports/decision-support-system-software-market-22343

agriculture to help farmers decide the appropriate time to plant and develop virtual factories to boost crop planning."[52] The **software simulation market** is experiencing significant growth. Market research by Markets to Markets finds that "the [global] market size is estimated to grow from USD 19.95 billion in 2024 to USD 36.22 billion in 2030 at a compound annual growth rate (CAGR) of 10.4%"[53] Grand View Research suggests a higher degree of market growth, increasing from USD 23.56 billion in 2024 to USD 51.11 billion by 2030, growing at a CAGR of 14.0% from 2025 to 2030.[54] The USA dominates this market. The cloud-based segment is expected to see the most growth, and healthcare is the largest application of this technology.[55] The **digital twin market** is projected to experience unprecedented growth within the next decade. Research and	real-time adjustments, improving accuracy and removing human intervention."[61] Adoption of cloud-based solutions: The rising prominence of cloud computing and cloud architectures are driving widespread adoption of simulation software and modelling tools.[62] The cloud-based segments of simulation software, decision-support systems, and modelling tools are becoming more prominent in the market(s).[63] According to Markets and Markets, "cloud-based simulation platforms enable organizations to run complex simulations without the need for on-premise infrastructure," thus reducing adoption costs and driving adoption.[64] Moreover, cloud-based software can be easier to maintain and update remotely based on client needs.[65] Government policy: There is a rise in government policies and programs, including cost-share programs and grants in support of sustainable agricultural practices, innovations, and commercial activities.[66] For example, the Sustainable Canadian Agricultural Partnership has set priorities and launched funding in support of sustainable agri-food initiatives across the country.[67] This program, among others, are driving demand for modelling tools and simulation software that can predict the impacts of policies, programs, and technologies on sustainability outcomes.	become rampant, increasing the chance of data loss."[74] The risks of cyberattacks may be especially concerning for farmer's, whom often reside on their farm, and who have complex biological systems, crops, and livestock at stake. As such, agricultural stakeholders including farmers may have concerns related to data ownership and privacy.[75] These concerns could slow adoption and/or market growth. Upfront cost: There are high initial costs associated with developing and deploying the tools.[76] Moreover, while simulation software and modelling tools may reduce long-term costs for end-users, the cost of software licences and training required to utilize the tool could slow adoption. This may be especially true for farmers. Availability of free, open-source tools: There are several free, publicly available modelling tools for agricultural

52 https://www.grandviewresearch.com/industry-analysis/decision-support-system-market-report
53 https://www.marketsandmarkets.com/Market-Reports/simulation-software-market-263646018.html
54 https://www.grandviewresearch.com/industry-analysis/simulation-software-market
55 https://www.grandviewresearch.com/industry-analysis/simulation-software-market
61 https://www.marketsandmarkets.com/ResearchInsight/emerging-trends-in-simulation-software-market.asp
62 https://www.marketsandmarkets.com/ResearchInsight/emerging-trends-in-simulation-software-market.asp
63 https://www.grandviewresearch.com/industry-analysis/simulation-software-market ; https://www.fnfresearch.com/3d-mapping-and-modeling-market ; https://www.marketsandmarkets.com/ResearchInsight/emerging-trends-in-simulation-software-market.asp
64 https://www.marketsandmarkets.com/ResearchInsight/emerging-trends-in-simulation-software-market.asp
65 https://www.grandviewresearch.com/industry-analysis/simulation-software-market
66 https://www.sciencedirect.com/science/article/pii/S1871678417300122?casa_token=3A_oECitipoAAAAA:Pu6MikjBNp5yM_6OLYMP2wl25QONeh27jQnXX2zYMsMT877-GzUPaRFD6Hu49eWUgf-ib4iQ-A
67 https://www.canada.ca/en/agriculture-agri-food/news/2023/03/sustainable-canadian-agricultural-partnership-launches-april-1-20230.html
74 https://www.marketsandmarkets.com/Market-Reports/simulation-software-market-263646018.html
75 https://cdn.prod.website-files.com/63a20f3f59f3bd3ff8cdd276/63bb8f42a09a600a03674bff_NCO-Policy-Brief-55-October-2022-Growing-Agri-Innovation-Lessons-from-Global-Innovation-Clusters.pdf
76 https://www.marketsandmarkets.com/Market-Reports/simulation-software-market-263646018.html

Markets expects this market to grow from USD 23.4 Billion in 2024 to USD 219.6 Billion in 2033, with a CAGR of 25.08%.[56] Agriculture is a growing "end-use" of digital twins, with digital twins being "employed for crop modelling, climate impacts simulations, and precision agriculture."[57] While the **3D mapping and modelling market** is currently smaller than the above markets (USD 5.37 Billion in 2023), it is growing at a rapid rate.[58] By 2032, the market is expected to be valued at USD 20.59 billion, with a CAGR of 16.10% between 2024 and 2032.[59] While agriculture is listed as a segment of this market, it is small compared to other sectors, including aerospace and defense, automotive and transportation, and healthcare. North America is generating the most revenue in this market. [60]	**Increased focus on resource efficiency and sustainability**: Government, consumers, and industry are working to increase resource efficiency and enhance environmental sustainability.[68] This includes a focus on reducing greenhouse gas emissions, and environmentally harmful inputs, including pesticides and herbicides. Simulation software and modelling tools are becoming increasingly beneficial for simulating, planning, and managing these sustainability initiatives.[69] **Regulatory compliance**: "Increasingly stringent legal requirements involving complex operational constraints are difficult to manage manually."[70] This is true for many industries, including agriculture. For example, a recent amendment to Bill C-59 is now requiring that environmental benefit claims be substantiated with adequate and proper testing.[71] Businesses that do not offer testing to back up environmental benefit claims face litigation risks associated with false advertising and greenwashing.[72] Tools that support predictive modelling and scenario generation (e.g., simulation software, decision support tools, 3D mapping and modelling, and digital twins) can help better understand how different scenarios, including the adoption of sustainable agricultural practices, may impact compliance.[73] Such tools may also offer proof of environmental benefit, protecting companies from greenwashing claims.	systems developed for "public good" as opposed to commercial profit (see Table 5 on commercial solutions). Many of these tools are developed for government, researchers, or sustainability champions. This is especially true for system-level agri-food modelling tools. Market growth may therefore be challenged by the availability of free tools and resources. **Narrow range of end-users:** While the broad markets described in this table (decision support systems, simulation software, digital twins, and 3D mapping and modelling) have a broad range of end-users, there are fewer end-users for a modelling tool specific to agri-food systems at a regional scale. The specificity of the agri-food modelling tools being developed could create challenges for market growth.

[56] https://www.researchandmarkets.com/reports/5936063/digital-twin-market
[57] https://www.researchandmarkets.com/reports/5936063/digital-twin-market
[58] https://www.fnfresearch.com/3d-mapping-and-modeling-market
[59] https://www.fnfresearch.com/3d-mapping-and-modeling-market
[60] https://www.fnfresearch.com/3d-mapping-and-modeling-market
[68] https://ictc-ctic.ca/reports/canadian-agrifood-sustainability
[69] https://www.marketsandmarkets.com/ResearchInsight/emerging-trends-in-simulation-software-market.asp
[70] https://www.giiresearch.com/report/imarc1675844-digital-twin-market-size-share-trends-forecast-by.html
[71] https://www.blg.com/en/insights/2024/07/false-advertising-and-greenwashing-bill-c-59-changes-to-competition-act#:~:text=Bill%20C-59%2C%20The%20Fall,environmental%20benefit%20claims%20(greenwashing)
[72] https://www.blg.com/en/insights/2024/07/false-advertising-and-greenwashing-bill-c-59-changes-to-competition-act#:~:text=Bill%20C-59%2C%20The%20Fall,environmental%20benefit%20claims%20(greenwashing)
[73] https://www.giiresearch.com/report/imarc1675844-digital-twin-market-size-share-trends-forecast-by.html

Stakeholder Positioning

Stakeholders are any individual, group, or organization that has an interest in, is affected by, or can influence the discovery, development, commercialization, acceptance and adoption of innovations. Stakeholders play a role in shaping research priorities, funding, knowledge translation and transfer (KTT), policy development, and the adoption of innovations that affect agricultural productivity, food security, sustainability, and rural economies or have concerns about ethical, social, economic, or environmental impacts. It is important to engage stakeholders as early as possible in the innovation process. Profiling stakeholders expands the scope and impact of innovation beyond commercialization and provides insights for broader applications of the innovation.

Table 7 represents a list of relevant stakeholder groups. Given the system-level nature of the modelling tool(s) being developed by the Just Transitions in Agri-Genomics research team, there is a diverse variety of stakeholders who can support and/or benefit from the project's success. Various stakeholder groups should be engaged along different stages of research and development, technology deployment, and commercial growth.

Table 7. Potential Stakeholders

Stakeholder Group	Description/Profile	Example
Farmers	While farmers may not have the capacity to leverage the modelling tool(s) directly due to resource constraints (e.g., time, money, skills), farmers remain a critical stakeholder group. The modelling tool(s) could help farmers understand which crops and technologies may support sustainable agricultural success under a changing climate. Efforts can be made to ensure that insights from the modelling tools are being transferred to farmers through other stakeholder groups, such as individuals working in extension and advisory services, researchers, non-profit organizations, and/or industry organizations. One way to directly engage farmers committed to sustainable agriculture is by working with the Agriculture and Agri-Food Canada (AFFC)-funded British Columbia Living Lab, which engages farmers in research on best management practices and agricultural innovations related to agricultural climate solutions.[77] AFFC has established 14 living labs across the country, spanning each province.[78] Collaborating with living labs across the country could also offer opportunities to scale the modelling tool(s) beyond BC.	Fruit and vegetable growers of British Columbia and Canada of varying sizes (E.g., BC Fresh Inc., Meadow Berry Farm, VegPro International). AFFC Living Labs (e.g., BC Living Lab).

[77] https://bclivinglab.ca/
[78] https://agriculture.canada.ca/en/environment/climate-change/agricultural-climate-solutions/agricultural-climate-solutions-living-labs

Government Policymakers	Policymakers within federal, provincial, and municipal governments are important end-users of the modelling tool(s). Local and provincial government may have the most interest in the tool(s) from an end-user perspective due to the regional nature of the tool. Municipalities (e.g., Fraser Valley Regional District) may have an interest in utilizing the tool for its ability to support rural land use planning and economic development initiatives related to agriculture. The federal government may have an interest in the tool, if it is expanded upon at a national level. Government policymakers could utilize the tool to design and develop policies and programs that will have the highest impacts on environmental sustainability (e.g., simulating the impacts of incentive programs on technology adoption and sustainability outcomes). One example of a government program that may benefit from utilizing the modelling tool is the Environmental Farm Plan, funded by the Government of Canada's Sustainable Agricultural Partnership.	Municipal governments (e.g., Fraser Valley Regional District) British Columbia Ministry of Agriculture and Food Agriculture and Agri-Food Canada
Regulatory Agencies	In addition to supporting government policymakers, the modelling tool may be able to support regulators that develop agricultural and environmental regulations, and guidelines. This group may benefit from using the tool to test the impacts of climate change and/or policy scenarios on compliance and/or develop new guidelines tailored to regional agri-food system changes.	Regulators of the Government of British Columbia's Environmental Management Act, and Code of Practice for Agricultural Environmental Management. Environment and Climate Change Canada
Standards Bodies	Literature on agri-food system modelling tools describes the need for standardization and validation of methods utilized to model agri-food systems – especially those that are augmented by AI (Sánchez et al., 2022). Both the Canadian Standards Association (CSA) and the International Organization for Standardization (ISO) are actively involved in developing standards for data-driven agriculture and digital agriculture. CSA has developed Canadian Mirror Committees to ISO Technical Committees, including ISO/TC 347:	ISO Technical Committee on ISO/TC 347: Data-driven agrifood systems. Canadian Standards Association (CSA), and the CSA mirror committee on ISO/TC 347 led by Marzan Habej-Bek.

	Data-driven agri-food systems.[79] ISO/TC 347 seeks to address interoperability challenges in sustainability models, metrics, and data in agrifood systems. The ICT should be aware of standards being developed for digital agriculture, including ISO/TC 347 to ensure that the modelling tool(s) align with incoming standards.	
Researchers and Academics	Researchers and academics present potential end-users for the modelling tool(s). Academic institutions may be willing to pay for licencing software or subscription models so that the tool can be utilized to inform research projects relevant to sustainable and localized agricultural systems under changing climate and policy scenarios. This may be true for other non-academic research institutes and public policy think tanks. Researchers working to generate data on agricultural systems may also benefit from using the tool(s) by inputting their data into the tool to receive modelling outputs on insights. In addition, researchers that are carrying out similar and/or complimentary research and development activities in other regions could present potential collaborators. For example, recent NSERC Alliance Grants have been awarded to researchers at McMaster University and McGill University to carry out agri-food system modelling[80]. From McMaster, Dr. Hassini is developing an "integrated digital platform" that will model how agri-food systems respond to stressors like climate change, labour shortages, and supply chain disruption. [81] From McGill, Dr. Adamchuk is developing a meta-systems model that could be used to inform farm management and agri-environmental policy design.[82] Both projects use similar methodologies and have similar objectives as the Just Transitions in Agri-Genomics research team, thus presenting potential research partners – especially for expanding and scaling the model at a national level.	Research Institutes and Public Policy Think Tanks (e.g., The Canadian Agri-Food Policy Institute, Farmers for Climate Solutions, Stratus Ag Research) Academic researchers (e.g., Dr. Hassini of McMaster University, Dr. Adamchuk of McGill University)

[79] https://www.csagroup.org/standards/areas-of-focus/agriculture-agri-food/#:~:text=CSA%20Group%20has%20established%20advisory%20groups%20to,and%20expertise%20and%20contributing%20to%20global%20standardization.
[80] https://www.nserc-crsng.gc.ca/ase-oro/Details-Detailles_eng.asp?id=782526 ; https://www.nserc-crsng.gc.ca/ase-oro/Details-Detailles_eng.asp?id=777789
[81] https://www.nserc-crsng.gc.ca/ase-oro/Details-Detailles_eng.asp?id=777789
[82] https://www.nserc-crsng.gc.ca/ase-oro/Details-Detailles_eng.asp?id=782526

Educational Institutions and Service Providers	Educational institutions and service providers pose potential end-users of the modelling tools. Due to the sophistication of the tool, post-secondary education institutions are most likely to leverage the tool for use in coursework on sustainable and localized agricultural systems under changing climate and policy scenarios. However, understanding how to use the tool and/or understanding insights from the tools could also inform K-12 education. For instance, educational services organizations, such as Agriculture in the Classroom Canada, or Trades and Transitions BC, could have interest in purchasing the software to inform programming about sustainable agriculture.	Post-Secondary Education Institutions and Agricultural Programs (e.g., Olds College of Agriculture and Technology, Farm Management and Technology Program at McGill University, University of Guelph Ontario Agriculture College, University of British Columbia Sustainable Agriculture and Environment (SAGE) Program). Education service providers (e.g., Agriculture in the Classroom British Columbia, Trades and Transitions, Regenerative Agriculture Program).
Extension & Advisory Services	Agricultural extension and advisory services represent important end-users and/or delivery partners for the modelling tool(s). These advisors often have a trusting relationship with farmers and may be able to effectively share insights from the modelling tools with farmers. Individuals and groups working in extension and advisory services can leverage the tool(s) to advise and support farmers in adapting to climate change, potentially by changing crops, or by adopting new technologies or best management practices.	Agrologists (e.g., BC Institute of Agrologists) Certified Crop Advisors Farm Consultants (e.g., Linden Lane Farms, Upland Agricultural Consulting) Provincial Extension Services (e.g., Government of British Columbia Extension Program) Advisory Services (e.g., Farm Management Canada, British Columbia Agriculture Council (BCAC)
Industry Organizations and Growers Associations	While extension and advisory services can utilize the modelling tool(s) to offer specialized recommendations for individual farmers, industry organizations and growers associations may be beneficial in disseminating regional insights from the tools. Organizations with a focus on sustainable agriculture may have a particular interest in utilizing the tool(s) and/or obtaining insights from the tool(s). For example, British Columbia Agriculture Council (BCAC) supports climate readiness initiatives for the BC agriculture sector, including working directly with government to develop policies and programs	Industry Organizations (e.g., British Columbia Agriculture Council (BCAC), Growers Associations (e.g., BC Strawberry Growers Association, BC Fruit Growers Association, Fruit and Vegetable Growers of Canada)

	that mitigate climate change. BCAC may be interested in leveraging the modelling tool to support their climate readiness initiatives. Growers associations representing the seven economically important crops (celery, broccoli, cauliflower, kale, strawberries, lettuce, and cabbage) in British Columbia identified by the Just Transitions in Agri-Genomics research team may be especially interested insights from the modelling tool(s).	
Indigenous Communities and Knowledge Holders	Indigenous communities have the potential to be an important stakeholder group, especially if the modelling tool is expanded at a national level. Indigenous communities could be interested in utilizing the tool to inform climate change-resilient crops and sustainable agricultural practices. These communities may also be interested in leveraging insights from the tools to support economic development initiatives, such as investments in certain agricultural technologies.	Indigenous Non-Profits and Agricultural Councils (e.g., B.C. Indigenous Advisory Council on Agriculture and Food (IACAF), National Circle for Indigenous Agriculture & Food, BC First Nations Climate Leadership Agenda)
Investors	Private investment can help to scale commercialization of the modelling tool in the private sector. Investors could include small Venture Capital (VC) firms, larger funds, and banks. Finding investors that can offer support beyond capital (e.g., marketing, commercialization, ecosystem development, and exit opportunities) is important.	AgTech Venture Capital Firms (e.g., Verdex Capital, Carrot Ventures, NYA Ventures, Nàdarra Ventures, Arctern Ventures) Farm Credit Canada (FCC) Agricultural Divisions of Banks (e.g., Agricultural banking at RBC, BMO, and CIBC)
Funding Bodies and Accelerators/Incubators	Funding bodies and granting agencies present a unique stakeholder group for the Just Transitions in Agri-Genomics research team. Their potential involvement is two-fold. Firstly, this stakeholder group could help grow and scale the modelling tool(s) by offering direct funding into the project's development and commercial growth or by supporting the project through accelerator/incubator services, if deemed necessary by the research group and i-Open Group. Secondly, funding bodies and granting agencies may also present potential end-users of the modelling tool. For example, some commercial solutions on the market offer modelling tools that map the return on investment (ROI) of programs and funding	Investment Agriculture Foundation of BC Canadian Food Innovation Network (CFIN) Genome Canada NSERC Canadian Agri-Food Automation and Intelligence Network (CAAIN) Foresight Canada

	initiatives.[83] If designed with this end-user in mind, the modelling tool could benefit funding bodies and granting agencies by allowing them to model and track the impacts of sustainable agriculture funding initiatives on key performance metrics (KPIs) like greenhouse gas emission reductions, biodiversity, carbon sequestration, soil health, revenue and more. Both private and public funding bodies and agencies could be interest in leveraging the tool too for this end-use.	Enterprise Machine Intelligence Learning Initiative (EMILI)
Farm Media and Science Communicators	Journalists, science communicators, and podcasters at the intersection of agricultural sustainability, technology, and policy present important stakeholders. This stakeholder group can help to disseminate insights from the tool(s), and market the tool(s) to relevant agricultural, government, and/or research-based audiences.	Journalists and News Organizations (e.g., Country Life BC, Ag Funder News) Podcasters (e.g., RealAgriculture Podcast, and/or Gateway Research Organization's podcast channels, including Wednesday Night Networking – Sustainable Agriculture, and Thursday Night Crop Talks)
Ag-Tech Companies	Agricultural technology (ag-tech) companies may be interested in using the modelling tool to understand technology adoption under different policy scenarios. Although the proposed tool does not assess the social, economic, or environmental impacts of technology adoption, incorporating this functionality could enhance its appeal to technology developers. By providing evidence-based projections of potential sustainability benefits, the tool could help ag-tech developers better position and market their technologies within the agricultural market.	Precision Agriculture Companies Farm Management Software Companies Vertical Agriculture and Controlled Environment Agriculture Companies Automation and Robotics Companies

[83] https://www.cibotechnologies.com/about/