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A Vegetable Farmer's Choice: Adoption of Soil Conservation Practices

A *Research* Report prepared for CAPI by Dislène Senan Sossou

Research Report

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The Canadian Agri-Food Policy Institute's mission is to lead policy development, collaborate with partners and advance policy solutions within agriculture and food

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Note from CAPI

CAPI recognizes the importance of fostering and mentoring the next generation of thought leaders emerging from Doctoral programs across Canada, who are working in multi-disciplinary fields. Through CAPI's Doctoral Fellowship program, CAPI offers a small, innovative group of young students the opportunity to apply their knowledge and expertise to some of agriculture's most critical policy issues.

The fourth cohort of CAPI's Doctoral Fellows (2024-2025) was tasked with focusing their research on policies needed to address pressures on Canada's land base and natural resources arising from agricultural production in the face of climate change, biodiversity loss, global population growth and food security concerns. This paper is the final deliverable of the program, showcasing the interdisciplinary nature of the fellows' research as it relates to Canadian vegetable farmers' decision-making processes in adopting soil conservation practices' adoption on agricultural lands.

This Fellowship is supported in part by the RBC Foundation through RBC Tech for Nature as part of CAPI's larger environmental initiative, Policies for Land Use, Agriculture and Nature (PLAN).

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Key Takeaways

- **Cover crops and multiple crops work together.** Vegetable producers in Canada often pair sustainable practices such as cover crops with multiple cropping, while reduced tillage and multiple cropping act as substitutes.
- **Soil fertility drives conservation and crop decisions.** Producers often prioritize soil health in the selection of vegetable crops and soil conservation practices.
- **Producers choose crops before deciding how much land to plant.** In terms of allocating land to vegetable crops, farmers decide which types of vegetable crops to cultivate prior to determining how much land to allocate to each.
- **Adoption of soil conservation practices follow different adoption patterns.** Farmers' decisions regarding adoption of soil conservation practices and selection of vegetable crops, are sometimes sequential, while other decisions take place at the same time. Understanding the decision process will allow policymakers to design incentive programs that balance environmental benefits, optimal land use and economic sustainability.
- **Economic and environmental goals don't always align on-farm.** There is a potential tension between economic sustainability (via succession planning) and environmental sustainability (via Environmental Farm Plans), suggesting that policymakers or advisors may need to balance both objectives when designing conservation programs.

List of acronyms

CCA: Canadian Census of Agriculture

EFP: Environmental Farm Plan

FMS: Farm Management Survey

NDV: Nutrient-demanding vegetable

SCPs: Soil conservation practices

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1. Introduction

In recent years, vegetable production in Canada has experienced a significant increase to respond to rising consumer demand and to reduce reliance on imports (AAFC, 2024). This growing demand for field vegetables highlights their importance in maintaining a healthy diet. While the expansion of vegetable production contributes to greater food autonomy and improves food security, it also raises environmental concerns, particularly about the sustainability of agricultural ecosystems. Vegetable production involving the intensive use of chemical inputs and agricultural mechanization, is one of the major sources of soil degradation through erosion, compaction, and nutrient loss (Lu, Powlson, Liang, Chadwick, et al., 2021; Lu, Powlson, Liang, Yao, et al., 2021; Marshall et al., 2021) .

Canadian farmers have long struggled with soil erosion, a process by which natural forces (wind, water) remove and transport away the top layer of soil. It is a critical issue that results in both environmental and farm-level economic costs. The continuous loss of topsoil reduces the soil's depth and negatively affects its physical and chemical properties necessary for plant growth, thereby reducing soil productivity (Duan et al., 2011). This degradation may lead to a decline in agricultural yields and farm profitability (Badreldin & Lobb, 2023; Ives & and Shaykewich, 1987). Soil erosion also contributes to the sedimentation of waterways, which reduces water quality. Research and policies have been designed to address these issues, and thus have promoted agri-environmental practices, especially soil conservation practices (SCPs).

Soil conservation practices protect soil against erosion and nutrient loss while improving its physicochemical properties, productivity and overall crop production. In terms of profitability, these practices can lead to higher crop yields and positive returns on investment. Adoption of SCPs, such as no-till, can lead to the reduction of production costs through reduced labor demand, herbicide, and chemical fertilizer use, and expenditure on machinery (Awada et al., 2016). SCPs are thus important for environmental sustainability and agricultural productivity and profitability. To promote higher adoption of SCPs among farmers, Canadian federal and provincial governments have more recently introduced various cost-share agri-environmental programs. The most widely used program is the Environmental Farm Plan (EFP) (Rudd et al., 2023). Although these programs are effective at encouraging SCPs, farmers and producers remain reluctant to fully adopt them. Depending on the region and crop specification, some practices have high adoption rates, while others face lower uptake (Shah et al., 2022). The main barriers to their adoption are financial constraints, implementation challenges, access to information, market access, non-targeted support, and farmers' perceptions (Potter et al., 2024; Shah et al., 2022; Wandel & Smithers, 2000).

Given the importance of vegetable production for global food security and its effect on land degradation, this study investigates what drives vegetable farmers to adopt SCPs and how these choices shape crop selection and land use, aiming to guide cost-effective policy support. The corresponding research questions are (i) What are the factors that condition the adoption of SCPs in various parts of Canada? (ii) Are adoption of SCPs and selection of vegetable crops, based on their soil nutrient requirements, simultaneous or sequential decisions? (iii) Does the adoption of SCPs influence vegetable crop acreage allocation? While the paper focuses on Canadian experience in farm-level soil conservation, the findings will inform strategic policies based on the key factors to consider in programs designed to boost adoption rates. It reviews empirical studies on drivers of SCPs adoption, emphasizing Canadian examples and relevance for vegetable farming. It presents data used and methods employed for data analysis. It discusses the main results and concludes with the implications of the findings for policy.

2. Background

Although numerous studies worldwide have looked at the elements affecting the adoption of soil conservation practices (SCPs), few have particularly examined the drivers of SCPs adoption for vegetable production in Canada. Research identifies four key drivers of SCP adoption in Canada: farmers' characteristics (e.g., education boosting no-till use in Quebec), farms' characteristics (e.g., larger Ontario farms adopting cover crops), financial considerations (e.g., income enabling crop rotation), and external factors (e.g., Prairie subsidies).

Farmers' characteristics include their socio-demographic characteristics, such as gender, age, farming experience, education, and their beliefs. Ghazalian et al. (2009) found that older farmers with high experience, wide exposure to various agricultural practices, or farmers with high degrees of education were more likely to adopt crop rotation in Chaudière watershed in Quebec. Potter et al. (2024) also mentioned that in Ontario, family links and concern for future generations were major adoption factors for medium and large-scale potato producers. Farmers who had emotional and family links to their property as well as a succession plan for future generations, were more likely to adopt SCPs to protect soil health and guarantee the long-term sustainability of their farms.

Farm characteristics that influence the adoption of SCPs include, among others, farm size and soil properties. Larger farmers in the Canadian prairies, are more likely to adopt conservation tillage (Davey & Furtan, 2008). In the Canadian prairies, farms with a high proportion of black and dark gray soil, compared with the ones with a high proportion of brown soil, are likely to adopt conservation tillage. Regarding financial considerations, efficiency and profitability of cover crops in vegetable rotation, are key drivers of their adoption among potato farmers in Ontario (Potter et al., 2024). Additionally, exogenous factors such as weather, social capital, participation in training sessions, extension activities, and enrollment in agro-environmental programs positively influence adoption of reduced tillage, cover crops and crops rotation in the Canadian prairies, Ontario and Quebec (Davey & Furtan, 2008; Ghazalian et al., 2009; Potter et al., 2024; Tamini, 2011).

It is also important to highlight that some studies assumed that SCPs are implemented independently while others showed that these practices can be used jointly because of their complementarity or substitutability nature (Ghazalian et al., 2009; Gong et al., 2021; Shah et al., 2022). In Ontario's grain farming, rotation with winter wheat, cover cropping, and no-till tend to be positively correlated (Shah et al., 2022). The complementary nature of SCPs adoption may have positive effects on soil properties. As far as we know, there are no studies that have investigated the joint adoption of SCPs in the context of vegetable production in Canada.

Finally, the adoption of SCPs may influence farmers' crop selection and acreage allocation. Farmers select crops for cultivation on a specific part of their farmland and decide the corresponding acreage to allocate, based on SCPs requirements and their beliefs about soil productivity (Orazem & Miranowski, 1994). In the context of vegetable production, some crops require a high level of soil nutrients for optimal growth, and their intensive production may negatively affect soil properties and health (Lu, Powlson, Liang, Chadwick, et al., 2021; Pessoa et al., 2024). Investigating the impact of SCPs adoption on land allocation for vegetable production is then critical to inform Canadian agricultural and land-use policies.

3. Methodology

This study investigates Canadian vegetable farmers' decisions as part of a causal chain involving three stages: the adoption of SCPs (Stage 1), crops choice (Stage 2), and land allocation (Stage 3). Using survey data and an econometric modelling approach, this study identifies key drivers at each stage. In the first stage of the decision process, a farmer is assumed to adopt a bundle of SCPs to restore and/or preserve the quality of his farmland, conditional on the current health status of the soils. At this stage, the analysis focuses on identifying key factors that influence the adoption of SCPs among vegetable farmers. The implementation of a SCP usually requires capital investment and hence a medium-to-long-term commitment. Conditional on the SCPs adoption, a farmer in the subsequent two stages selects the types of crops to cultivate, considering their specific soil nutrients requirements. To address the second research question, the study assesses whether SCPs adoption and vegetable crops choice decisions are simultaneous or sequential. Conditional on cultivated crops and the selected SCPs, a farmer in the third stage determines the land size to allocate to each selected crop. The empirical strategy employed will assess whether crops selection and acreage allocation are sequential or simultaneous decisions, as well as key determinants of acreage allocation.

Combined data from the 2021 Canadian Census of Agriculture (CCA) and Farm Management Survey (FMS) capture practices across Canada's vegetable farms. The FMS is a survey that takes place every two to five years. The CCA takes place every five years and targets all "census farms" in Canada at the national, provincial and sub provincial levels. The soil conservation practices adopted by farmers surveyed are reduced tillage, double or triple cropping, cover crops, and green manure. No-tillage and reduced tillage are conservation tillage practices that minimize soil disturbance and maintain crop residues on the soil surface. Multiple cropping is defined as a farming system that involves growing two or more crops in succession within a single year on the same piece of land. Cover crops are grasses, legumes, and other forages planted for seasonal vegetative cover (U.S. Department of Agriculture, 2024). Green manuring is a practice that incorporates (in situ/harvested elsewhere) undecomposed green material into soil to improve its fertility and increase the productivity of subsequent crops. Vegetable crops are grouped into three categories, namely high nutrient-demanding vegetables (NDV) (i.e. broccoli, brussels sprout, cabbage, etc.), medium nutrient-demanding vegetables (NDV) (i.e. asparagus, beet, cucumber, etc.), and low nutrient-demanding vegetables (NDV_ (i.e. carrot, lettuce, rutabaga, etc.) (Weill & Duval, 2009).

4. Results

The data set used in this study identifies across all Canadian regions, 355 vegetable farms, where at least one vegetable crop is cultivated at the farm level.

4.1 Overview of vegetable production

On a national scale, vegetables are largely produced in Ontario which accounts for 49.2% of total cultivated area, followed by Quebec (36.8%), the Prairie provinces (5.3%) and the Atlantic provinces (3.6%). These production patterns reflect the importance of favourable soil conditions for vegetable farming. For instance, the Monteregie region in Quebec produces a large share of vegetable crops on organic soils, which are extremely productive. Moreover, vegetable crops are largely produced in southern Ontario, particularly in the regions along the Lake Erie and Ontario shorelines with fertile soils.

In terms of crop types, among the 355 farms, 54% cultivated high NDV, while 45% and 65% cultivated medium and low NDV, respectively. Additionally, 18.86% of farms cultivated all three categories of vegetable crops. The high level of low NDV production may be explained by their function as intermediate crops in rotation and multiple cropping systems.

4.2 Regional SCPs adoption

Among the four soil conservation practices examined, green manure and multiple cropping exhibit the **highest overall adoption rates**, while reduced tillage and cover crops have the **lowest adoption rate**.

Among the sampled farmers, (one respondent per farm), 27% claimed to use reduced tillage or no-tillage for their most common type of vegetable crops. However, 85% of respondents implemented double or triple cropping. The percentage of respondents who planted cover crops (fall or winter) and green manure are respectively 59% and 92%. The high adoption rate of green manure is due to its ability to improve soil health, reduce reliance on synthetic fertilizers, enhance yield productivity and therefore lower overall production costs.

Vegetable producers in Quebec exhibit the highest adoption rate of reduced tillage at 40%, followed by Ontario at 23.33%, while other provinces report a lower rate of 12.50%. This implies that vegetable producers in Quebec are more likely to implement reduced tillage compared to those in other regions. The main explanation is that the Quebec government provides better incentives that support this practice (Statcan, 2018). Regarding the use of cover crops, the adoption rates are 53.33% in Ontario, 60% in Quebec and 62.50% in other provinces. The high adoption rate observed in other provinces particularly in the Prairies, is attributed to positive spillover effects from earlier uptake of cover crops by farmers in neighboring US states and in Eastern Canada (CAPI, 2021).

4.3 What are the key determinants of SCPs adoption?

The **determinants of reduced or no-tillage adoption** are access to custom operators, monetary value of land and buildings, and farm's location in Quebec. In the case of **multiple cropping**, key determinants include writing a succession plan, access to custom operators, area size used for chemical fertilizers, sales to wholesalers, and farm's location in Quebec or Ontario. Additionally, the adoption of **cover crops** is associated with the area cultivated for high NDV and the use of family labor. Lastly, direct on-farm sales, sales to retailers, and sales to wholesalers are key factors influencing the adoption of **green manure**.

Estimation results related to farmer's characteristics show that writing a succession plan increases the likelihood of adopting multiple cropping by 14.7%. Getting technical assistance from custom operators increases the probability of adopting multiple cropping by 6.6%; while it decreases the probability of adopting reduced or no-tillage by 16.2%. In the literature, Tamini (2011) found that advisory services positively influenced the likelihood of adopting conservation tillage among farmers in Quebec. The negative effect of technical assistance may be justified by an inadequate number or shortage of technical agents (Belachew et al., 2020). Additionally, an increase of one acre of the area used for chemical fertilizer increases the probability of adopting multiple cropping by 0.014%. This result contradicts many studies that found that SCPs such as conservation tillage, cover crops, crop rotation, intercropping are not associated with a high use of chemical fertilizer (Fuglie, 1999; Karasawa, 2024).

Considering farms' financial assets, a one-dollar increase in monetary value of land and buildings is associated with a 0.05% increase in the probability of adopting reduced or no-tillage. An explanation is that adopting no-tillage often requires investment in new machinery which are expensive. In line with Wandel & Smithers (2000), this result indicates that large-scale farmers are more likely to adopt reduced or no-tillage. Moreover, an increase in family labor of one worker increases the likelihood of adopting cover crops by 2.5%. This result matches with the findings of Leyva et al. (2007). However, Win et al. (2025) reported that a shortage of labor tends to increase the likelihood of using labor-saving technologies such as reduced-tillage equipment.

In terms of farms' management practices, an increase of farm size allocated to high NDV by one acre, decreases the probability of adopting cover crops by 0.1%. Some potential economic factors such as vegetable revenues or opportunity costs may explain this negative relationship (Moore et al., 2016). On the contrary, Wang et al. (2019) found that the number of crop acres positively affects SCPs adoption decisions. Results related to accessing a market, and farm contracts indicate that selling production directly from a farm increases the adoption of green manure by 7.4%. Selling production to retailers decreases the probability of adopting green manure by 9.5%. Selling production to wholesalers decreases the probabilities to adopt multiple cropping and green manure respectively by 9% and 7.7%. This result implies that recent policy to promote producers' direct sales to consumers may enhance good practices adoption due to income increases. Miller (1995) explained farm contracts that reduce soil conservation are the ones that restrict farmer autonomy and focus on short-term gains. Regarding exogenous factors, farmers in Quebec are 3.28% more likely to adopt conservation tillage compared to those in other Canadian provinces. In contrast, farmers in Quebec and Ontario are 2.03% and 2.38% less likely, respectively, to adopt multiple cropping compared to farmers in other provinces.

4.4 Assessing the complementarities of SCPs

In the context of vegetable production on Canadian farms, certain soil conservation practices are complementary, while others act as substitutes.

Cover crops are **complementary** to multiple cropping and green manure, providing several benefits to the ecosystem. Conversely, multiple cropping serves as a **substitute** for reduced tillage, suggesting that farmers face constraints when adopting both practices simultaneously, particularly due to weed management challenges.

Relationships between soil conservation practices are consistent with findings from other studies on grain production in the United States (Peterson et al., 2021; Sweeney et al., 2022). Combined use of cover crops and multiple cropping adoption reduces reliance of chemical fertilizers, improves nutrient cycling and increases yield (Karasawa, 2024). The observed substitution between reduced tillage and multiple cropping may explain the low adoption rates of reduced tillage and the relatively high adoption of multiple cropping in Quebec and Ontario. Farmers implement multiple cropping over reduced tillage due to weed management and other operational challenges commonly associated with conservation tillage (Adhikari et al., 2023).

4.5 Are the adoption of SCPs and the selection of vegetable types sequential or simultaneous decisions?

Farmers' decisions regarding SCPs and NDV selection follow different adoption patterns. Some decisions are sequential, while others are simultaneous.

Sequential decisions: Practices such as reduced tillage and multiple cropping are typically adopted prior to selecting low NDV.
Simultaneous decisions: Adoption of SCPs such as reduced tillage, multiple cropping, cover crops or green manure occurs simultaneously with the selection of vegetable characterized by high or medium soil nutrient demand.

Simultaneous adoption of SCPs with crops selection suggests that these decisions are influenced by market access, profitability, and farm constraints. **Moreover, adoption of SCPs influences the likelihood of cultivating vegetables with high, medium or low soil nutrient demand, in distinct ways.** Certain practices such as reduced tillage and the use of cover crops may discourage the cultivation of high NDV, necessitating policy interventions to maintain farm profitability. Multiple cropping and cover crops appear to support the cultivation of medium NDV, whereas the adoption of green manure appears to discourage it. Regarding farming low NDV, reduced tillage may encourage the cultivation of low NDV while multiple cropping may discourage it.

The estimation results show that writing an environmental farm plan, farm irrigation and selling harvested production from farms are the key determinants of the cultivation of high NDV. On the other hand, selling harvested production to retailers or wholesalers, or using nonfamily labor influences positively the probability of cultivating medium NDV. Writing a succession plan, access to custom operators, farm irrigation, the use of chemical fertilizers, agriculture expenditure and selling harvested production directly from the farm influence negatively the probability of cultivating this type of vegetables. According to low NDV, writing a succession plan and access to custom operators are positive factors impacting their cultivation. The negative factors include writing an environmental plan, farm irrigation, and selling harvested production to wholesalers or processors. One explanation might be that these crops are seen as already protecting against soil degradation and promoting sustainable production practices and vegetable producers are less inclined to invest more.

4.6 Is the selection of vegetable types and the allocation of acreage to them, a sequential or simultaneous decision?

As expected, crop selection and acreage allocation follow a **sequential** decision-making process.
The determinants of land allocation to vegetables in Canadian farms include access, technical assistance, labor composition, environmental practices, irrigation, and financial assets.

Access to technical assistance increases land allocation to high NDV while reducing land for low NDV. This suggests that access to specialized support may improve farmers' ability to manage higher-nutrient demanding crops. Farmers with succession plans allocate more land to medium NDV crops, while those with environmental farm plans allocate less. Therefore, farmers engaged in succession planning may prioritize market-oriented or high-value crops production to ensure farm continuity for future generations. Conversely, EFPs may encourage the cultivation of crops that better align with conservation objectives. These findings highlight a potential tension between economic sustainability (via succession planning) and environmental sustainability (via EFPs), suggesting that policymakers or advisors may need to balance both objectives when designing conservation programs. Regarding farms' characteristics, irrigation may be associated with a reduction in NDV acreage. In terms of financial assets, the results suggest that wealthier farmers may shift away from more intensive high-input crops (high and medium NDV) towards less resource-intensive crops (low NDV). Additionally, farms using both family and non-family labor increase land allocation to medium NDV, while reliance on non-family labor reduces land allocation to high NDV. Results related to market access show that farming contracts with wholesalers encourage high land allocation to high NDV, while contracts with processors favor land allocation to low NDV crops, suggesting that market structure strongly shapes production choices. These findings are consistent with other studies which find that advisory services, labor availability, farm irrigation and market structure positively affect crops acreage allocation (Allen, 2014; Anbaw & Phogella, n.d.; Gautam et al., 2024; Kudadze et al., 2019).

The geographic farm location is also a key determinant of vegetable acreage allocation. Compared to other provinces, farmers in Quebec tend to allocate 10.5% more land to medium NDV and 14.2% less land to low NDV. Farmers in Ontario (British Columbia) tend to allocate 19.4% (14.6%) and 9.7%

(3.5%) more land to high NDV and medium NDV respectively than farmers in other provinces. Depending on the soil types, farmers tend to allocate 29.1% (18.2%) less land to low NDV.

5. Policy Implications

This study investigates factors that drive farmers' simultaneous adoption of four SCPs, crops selection and acreage allocation for vegetable production in Canada. Overall, the findings suggest that effective policies should account for farmers' crop specialization, and the specific soil nutrient requirements of cultivated vegetables, to promote SCPs adoption and optimal farmland use. The key policy recommendations derived from the findings are outlined below:

- The findings on the interdependence between SCPs highlight the importance of encouraging the adoption of complementary practices while addressing the limitations of substitutable ones, to support broader uptake among farmers.
- Design soil conservation programs that balance economic and environmental sustainability. Adoption of SCPs influences vegetable selection differently. Therefore, policy measures should integrate the support of SCPs with crop requirements in terms of soil nutrients.
- Understanding the decision process from SCP adoption to crop acreage allocation will allow policymakers to design incentive programs that balance environmental benefits, optimal land use and economic sustainability.
- The insights related to determinants of acreage allocation highlight the need for tailored agricultural policies that:
  - Expand technical assistance and market access for high NDV to improve profitability,
  - Enhance supply chain integration, connecting farmers with wholesalers or processors that favor SCP-grown crops,
  - Design irrigation and incentives policies for a balanced land-use strategy,
  - Enhance labor policies to sustain medium and high NDV production, ensuring workforce stability and efficiency.

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7. Appendix

8.1 Multivariate Probit (MVP) Model

This study examines four soil conservation practices (SCPs) adopted by farmers surveyed across Canada provinces: reduced tillage (rt), double or triple cropping (mc), cover crops (cc), green manure (gm). Let an arbitrary i^{th} farmer ($i = 1, \dots, N$) who faces the decision of whether to adopt or not to adopt the k^{th} SCP ($k = rt, mc, cc, gm$). Let us denote U_i^k a farmer "i" utility when he adopts a SCP "k"and U_i^0 his utitily when he does not adopt it. Based on random utility framework (Adesina & Chianu, 2002; Ghazalian et al., 2009; Rahm & Huffman, 1984), the farmer adopts a SCP "k" when the utility derived from its adoption exceeds the utility derived from non-adoption. In other words, the net benefit a farmer gains from adopting a SCP "k", y_{ik}^* ,must be greater than zero, $y_{ik}^* \equiv U_i^k - U_i^0 > 0$. The latent (unobserved) variable y_{ik}^* is function of observed characteristics that influence farmer's adoption decisions such that:

$$y_{ik}^* = \beta_i^k . X_i + \varepsilon_i^k, \quad k = rt, mc, cc \text{ } and \text{ } gm \tag{1}$$

The vector of observed characteristics X_i includes farmers' attributes, farm characteristics, management practices, assets, and exogenous factors. The vector β_i^k includes coefficients associated with the adoption of the SCP "k" and ε_i^k is an error term which embodies unobservable factors conditioning adoption. Given the unobserved nature of y_{ik}^*, the estimations of SCPs adoption are based on common use of dummy variables in literature. Let us consider the observes outcome y_{ik} which takes the value of one if a farmer adopts a SCP "k" and zero otherwise as follows:

$$y_{ik} = \begin{cases} 1 \text{ } if \text{ } y_{ik}^* > 0 \\ 0 \text{ } if \text{ } otherwise \end{cases}; \quad k = rt, mc, cc \text{ } and \text{ } gm \tag{2}$$

Estimating univariate probit or logit models for the adoption of each of the four SCPs is likely to result in inefficiencies. This inefficiency arises from the fact that farmers' decisions regarding the adoption of conservation agricultural practices are not mutually exclusive. In particular, farmers often adopt multiple practices because these practices may complement or substitute one another in terms of their benefits for soil health and profitability (Canales et al., 2020; Gong et al., 2021). Moreover, unobserved farmers characteristics may simultaneously influence the adoption of different conservation practices, which leads to correlated error terms across the four separate adoption equations. The most appropriate model for estimating the adoption of multiple technologies, as expressed in equation (5), is the multivariate probit (MVP) model. Widely used in (Apio et al., 2023; Kolady et al., 2021; Oladimeji et al., 2020), the MVP model addresses the issue of endogeneity resulting from error term correlation. The error terms in latent equation (4) jointly follow a multivariate normal (MVN) distribution with zero conditional mean and variance normalized to unity, i.e. $(\varepsilon_{rt}, \varepsilon_{mc}, \varepsilon_{cc}, \varepsilon_{gm}) \sim MVN(0, \omega)$ and the symmetric covariance matrix ω is given by:

$$\omega = \begin{bmatrix} 1 & \sigma_{rtcc} & \sigma_{rtcc} & \sigma_{rtgm} \\ \sigma_{mcrt} & 1 & \sigma_{mccc} & \sigma_{mcgm} \\ \sigma_{ccrt} & \sigma_{ccmc} & 1 & \sigma_{ccgm} \\ \sigma_{gmrt} & \sigma_{gmmc} & \sigma_{gmcc} & 1 \end{bmatrix}$$

8.2 Multivariate fractional (MVF) model

Let the dependent variable s_i for the i^{th} observation be a vector of fractional values, such that:

$$S_i = (S_{i1}, \ldots, S_{iv})$$

Where S_{iv} represents the proportion of cultivated area for the v^{th} crops type by farmer i. Each dependent variable S_{iv} is the proportion of total cultivated area for horticultural crops, with $S_{iv} \geq 0$ and $\sum_{v=1}^{V} s_{iv} = 1$. An appropriate method to deal with fractional (not binary), bounded and unit-sum nature of these outcomes is the use of nonlinear conditional mean function $G(.)$ (Papke & Wooldridge, 1996). For each univariate dependent variable, the conditional mean is defined as follows:

$$E(S|X) = G(X\beta) \qquad (3)$$

Where the nonlinear function $G(.)$ satisfies $0 \leq G(.) \leq 1$. The vectors X and β include respectively the explanatory variables and the parameters to estimate. The proportions are not mutually exclusive, as farmers can cultivate one or more crops. Considering this assumption, this study employs a multivariate fractional (MVF) model to assess what factors influence crops acreage allocation. The MVF model with logit specification is expressed as:

$$E(S_v|X) = G_v = \frac{\exp\,(X.\beta_v)}{\sum_{l=1}^{V} \exp\,(X.\beta_l)}, v = 1, \ldots, V \qquad (4)$$

The model is estimated for proportions of acres devoted to high nutrient-demanding vegetables ($v = 1$), medium nutrient-demanding vegetables ($v = 2$), low nutrient-demanding vegetables ($v = 3$), and other horticultural crops ($v = 4$). This study considers four types of horticulture crops, i.e. $V = 4$. The nonlinear conditional mean $G_v = G_v(X\beta)$ satisfies $0 \leq G_v(.) \leq 1$ for all v, and $\sum_{v}^{V} G_v = 1$. The index l corresponds to each possible alternative for crops selection. The sum over l in the denominator ensures the probabilities sum to one across all alternatives. The parameters β will be estimated by maximizing the Bernoulli log-likelihood function, expressed as follow:

$$\hat{\beta} = LL(\beta) = \sum_{i=1}^{N} \log(L_i(\beta))$$

With $\log L_i(\beta) = \sum_{v=1}^{V} \mathrm{S_{iv}}.\log G_{iv} = \sum_{v=1}^{V-1} \mathrm{S_{iv}}.\log(\frac{G_{iv}}{G_{iV}}) + \log(G_{iV})$; and $G_{iV} = 1 - \sum_{v=1}^{V-1} G_{iv}$. Since the probabilities must sum 1, V – 1 will be modeled to avoid perfect multicollinearity.

Figure 1: Sequential decision process of SCPs adoption and crops selection

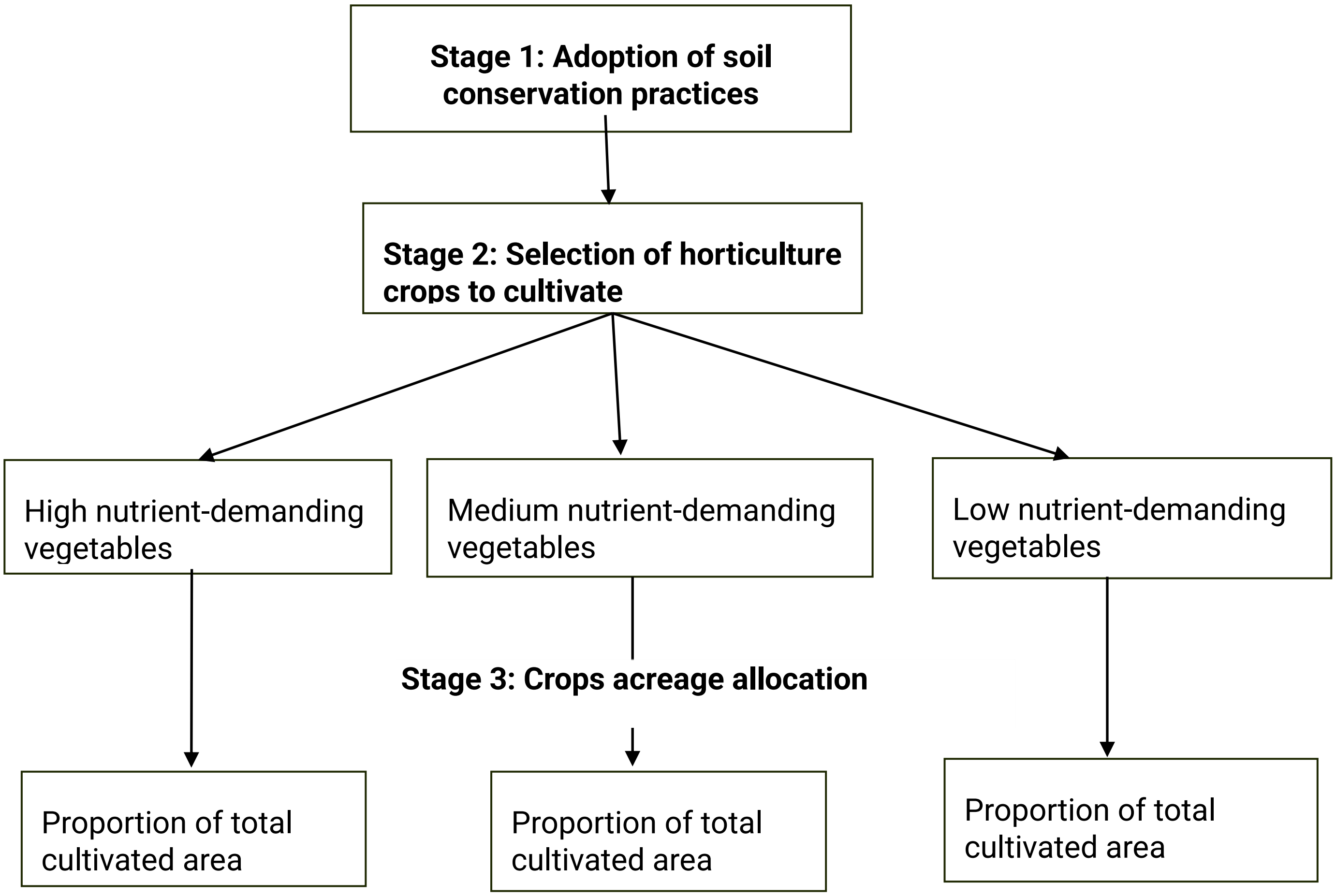

Table 1: Classification of nutrient-demanding vegetables

High nutrient-demanding vegetables	**Medium nutrient-demanding vegetables**	**Low nutrient-demanding vegetables**
• Broccoli • Brussels sprout • Cabbage • Cauliflower • Chinese cabbage • Pepper • Squash and zucchini • Tomato • Celery	• Asparagus • Beet • Cucumber • Pumpkin • Shallot and green onion • Dry onion • Radish	• Carrot • Lettuce • Rutabaga and turnip • Green and wax bean • Green pea

Table 2: Description of variables included in the estimation models

Variable	Description	Expected sign	Mean (S.D.)
Dependent variables			
Adoption of reduced tillage	Dummy variable that takes the value 1 if Between October 2020 and September 2021, farmer used no till or reduced till for his most common type of vegetable crop, and 0 otherwise.		0.27 (0.44)
Adoption of multiple cropping	Dummy variable that takes the value 1 if Between October 2020 and September 2021, two or three crops were grown at different times on the same land within a field i.e., double or triple cropped, and 0 otherwise.		0.85 (0.37)
Adoption of cover crops	Dummy variable that takes the value 1 if between October 2020 and September 2021, farmer planted cover crops (fall or winter) after harvest; =0 otherwise		0.59 (0.49)
Adoption of green manure	Dummy variable that takes the value 1 if between October 2020 and September 2021, farmer planted green manure crops in spring for his most common type of vegetable crops; =0 otherwise		0.92 (0.28)
Cultivation of high nutrient-demanding vegetables (NDV)	Dummy variable that takes the value 1 if farmer planted high nutrient-demanding vegetables, and 0 otherwise.		0.54 (0.50)
Cultivation of medium nutrient-demanding vegetables	Dummy variable that takes the value 1 if farmer planted middle nutrient-demanding vegetables, and 0 otherwise.		0.45 (0.50)
Cultivation of low nutrient-demanding vegetables	Dummy variable that takes the value 1 if farmer planted low nutrient-demanding vegetables, and 0 otherwise.		0.65 (0.48)
Farm area cultivated for high NDV	Farm area (acres) cultivated for high nutrient-demanding vegetable crops		40.05 (105.50)
Farm area cultivated for medium NDV	Farm area (acres) cultivated for medium nutrient-demanding vegetable crops		22.62 (60.65)
Farm area cultivated for low NDV	Farm area (acres) cultivated for low nutrient-demanding vegetable crops		50.49 (108.44)
***Explanatory variables**: Farmers' characteristics*			
Writing succession plan	Dummy variable that takes the value 1 if farmer has a written succession plan in place, and 0 otherwise	+	0.83 (0.37)
Developing a formal environmental farm plan	Dummy variable that takes the value 1 if farmer developed a formal environmental farm plan, and 0 otherwise	+	0.56 (0.50)
Custom operators	Dummy variable that takes the value 1 if farmer used custom operators to perform farm work on this operation related to crop or livestock production, and 0 otherwise	+	0.66 (0.47)
***Explanatory variables**: Farms' characteristics*			
No natural vegetation on operation	Dummy variable that takes the value 1 if there is no natural vegetation on operation, and 0 otherwise	+/-	0.66 (0.48)
Irrigation system on the farm	Dummy variable that takes the value 1 if there is an irrigation system on the farm.		0.38 (0.49)
***Explanatory variables**: Farms' assets*			

Total agricultural expenditure	Total agricultural expenditure (CAD) for the farm.	+	1504127 (2965470)
Total monetary value of land and buildings	Total monetary value (CAD) of land and buildings.	+	8597335 (11658545)
Total number of family workers	Total number of family workers who were issued a T4 slip	+	1.50 (2.11)
Total number of non-family workers	Total number of workers (without family labor) who were issued a T4 slip	+	2.38 (4.96)
***Explanatory variables**: Farms' management practices*			
Farm area used for chemical fertilizer	Farm area (acres) where chemical fertilizer is applied.	+/-	330.15 (577.26)
Selling the harvest on the farm	Dummy variable that takes the value 1 if farmer sold the harvested production directly on the farm.	+/-	0.24 (0.43)
Selling the harvest to wholesalers	Dummy variable that takes the value 1 if farmer sold the harvested production to wholesalers.	+/-	0.42 (0.49
Selling the harvest to retailers	Dummy variable that takes the value 1 if farmer sold the harvested production to retailers.	+/-	0.34 (0.47)
Selling the harvest to processors	Dummy variable that takes the value 1 if farmer sold the harvested production to processors.	+/-	0.38 (0.49)
***Explanatory variables**: Exogenous factors*			
Farm located in Quebec	Dummy variable that takes the value 1 if farm operation located in Quebec; and 0 otherwise	+/-	0.35 (0.48)
Farm located in Ontario	Dummy variable that takes the value 1 if farm operation located in Ontario; and 0 otherwise	+/-	0.42 (0.49)
Farm located in BritishColumbia	Dummy variable that takes the value 1 if farm operation located in British Columbia; and 0 otherwise	+/-	0.15 (0.36)

Table 3: Determinants of soil conservation practices (SCP)

Variables	Reduced tillage Coeff.	Multiple cropping Coeff.	Cover crop Coeff.	Green manure Coeff.
Farmers' characteristics				
Writing succession plan	-0.002 (0.196)	0.580*** (0.212)	0.217 (0.196)	0.161 (0.260)
Developing a formal environmental farm plan	0.222 (0.174)	-0.022 (0.195)	-0.068 (0.163)	-0.123 (0.240)
Custom operators	-0.535***(a) (0.166)	0.298* (0.178)	0.192 (0.161)	0.351 (0.216)
Farms' characteristics				
No natural vegetation on operation	0.060 0.174)	0.0750 (0.183)	-0.117 (0.170)	0.065 (0.202)
Irrigation system on the farm	0.261 (0.199)	-0.108 (0.222)	0.303 (0.190)	-0.297 (0.249)
Farm area used for chemical fertilizer	0.028 (0.037)	0.064* (0.039)	0.000 (0.034)	-0.009 (0.049)
Farms' assets				
Total agricultural expenditure	- 0.077 (0.080)	0.008 (0.079)	0.017 (0.076)	0.085 (0.096)
Total monetary value of land and buildings	0.176* (0.090)	0.016 (0.084)	-0.085 (0.080)	-0.016 (0.099)
Total number of family workers	-0.010 (0.045)	0.003 (0.043)	0.067* (0.040)	-0.008 (0.046)
Total number of non-family workers	-0.009 (0.019)	-0.030 (0.018)	-0.012 (0.015)	-0.013 (0.020)
Farms' management practices				
Farm area cultivated for high NDV	-0.002 (0.001)	0.001 (0.001)	-0.002* (0.001)	0.000 (0.001)
Selling the harvest on the farm	0.120 (0.212)	0.320 (0.231)	0.124 (0.208)	0.679** (0.330)
Selling the harvest to wholesalers	-0.020 (0.200)	-0.261 (0.212)	-0.148 (0.187)	-0.617** (0.255)
Selling the harvest to retailers	-0.108 (0.187)	-0.408** (0.197)	-0.013 (0.181)	-0.542** (0.245)
Selling the harvest to processors	0.095 (0.161)	-0.165 (0.196)	-0.014 (0.168)	-0.118 (0.197)
Exogenous factors				
Farm located in Quebec	1.132*** (0.351)	-0.880* (1.452)	-0.408 (0.353)	-1.019 (0.495)
Farm located in Ontario	0.616 0.356)	0.6496** (0.344)	-0.442 (0.346)	-0.601 (0.495)
Farm located in British Columbia	0.430 (0.428)	-0.695 (0.498)	-0.336 (0.393)	0.013 (0.643)
Constant	3.093 (1.298)	1.031 (3.284)	1.427 (1.194)	1.596 (1.693)
Observations	350	350	350	350
Log Likelihood (full model)	-2083.668			
Prob > chi2	0.0000			

Note: (a) ***, **, * indicate significance at the 1%, 5%, and 10%, respectively. (b) The semi-elasticities related to logarithmic variables are reported.

Table 4: Correlation between SCPs (coefficients from MVP model)

Correlation between practices	Correlation coefficients
rho21 (Multiple cropping, Reduced tillage)	-0.334***
	(0.104)
rho31 (Cover crop, Reduced tillage)	-0.112
	(0.101)
rho41 (Green manure, Reduced tillage)	-0.187
	(0.120)
rho32 (Cover crop, Multiple cropping)	0.276***
	(0.093)
rho42 (Green manure, Multiple cropping)	0.107
	(0.120)
rho43 (Green manure, Cover crop)	0.523***
	(0.089)

Likelihood ratio test of rho21= rho31 = rho41= rho32= rho42 = rho43= 0

Chi2(6) = 2937.59
Prob > chi2 = 0.0000

Note: (a) ***, **, * indicate significance at the 1%, 5%, and 10%, respectively.

Table 5: Determinants of vegetables cultivation

Variables	High NDV[(a)] Coeff	Medium NDV Coeff	Low NDV Coeff
Farmers' characteristics			
Writing succession plan	1.265 (0.770)	-1.480*** (0.479)	1.158** (0.585)
Developing a formal environmental farm plan	0.533*[(b)] (0.287)	-0.044 (0.218)	-0.583** (0.243)
Custom operators	-0.925 (0.603)	-0.824* (0.434)	1.372*** (0.496)
Farms' characteristics			
Irrigation system on the farm	2.795*** (0.566)	-1.189*** (0.267)	-0.542* (0.309)
Farm area used for chemical fertilizer	0.108 (0.077)	-0.146** (0.056)	0.077 (0.066)
Farms' assets			
Total agricultural expenditure	-0.209 (0.128)	0.040 (0.089)	0.099 (0.092)
Total monetary value of land and buildings	-0.126 (0.170)	0.057 (0.116)	-0.093 (0.141)
Total number of family workers	0.274 (0.109)	-0.125** (0.058)	0.068 (0.078)
Total number of non-family workers	-0.096 (0.040)	0.104*** (0.026)	-0.029 (0.031)
Farms' management practices			
Selling the harvest on the farm	1.785*** (0.451)	-0.497* (0.284)	0.087 (0.319)
Selling the harvest to wholesalers	-0.463 (0.399)	0.584** (0.283)	0.030 (0.311)
Selling the harvest to retailers	-0.048 (0.387)	0.460* (0.271)	-0.783** (0.324)
Selling the harvest to processors	0.363 (0.282)	0.098 (0.201)	-0.512** (0.233)
Adoption of reduced tillage [(d)]	-15.318*** (2.816)	-1.204 (1.754)	7.772** (2.039)
Adoption of multiple cropping [(e)]	0.957 (3.832)	7.443*** (2.543)	-8.592** (3.127)
Adoption of cover crops [(f)]	-17.594*** (3.597)	5.753*** (1.622)	0.567 (2.151)
Adoption of green manure [(g)]	0.139 (2.167)	-3.270* (1.758)	2.599 (2.106)
Exogenous factors			
Farm located in Quebec	1.879 (1.244)	2.666*** (0.788)	-3.002*** (0.868)
Farm located in Ontario	-0.121 (1.186)	3.233*** (0.710)	-2.859*** (0.799)

Farm located in British Columbia	0.594 (0.914)	2.388*** (0.559)	-1.373** (0.604)
Constant	15.050*** (5.388)	-8.177** (3.216)	4.450 (3.785)
Observations	350	350	350
Log Likelihood (full model)	-1795.7908		
Prob > chi2	0.0000		

Note: (a) NDV means nutrient-demanding vegetables. (b) ***, **, * indicate significance at the 1%, 5%, and 10%, respectively. (c) The semi-elasticities related to logarithmic variables are reported. (d), (e), (f), and (g) represent the predicted probabilities from the estimations of reduced tillage, multiple cropping, cover crop, and green manure adoption, respectively.

Table 6: Determinants of vegetables acreage allocation

Variables	Acreage of High NDV[(a)]	Acreage of Medium NDV	Acreage of Low NDV
	M. E.	M. E.	M. E.
Farmers' characteristics			
Writing succession plan	-0.046 (0.035)	0.091*** (0.028)	-0.045 (0.029)
Developing a formal environmental farm plan	0.015 (0.029)	-0.056** (0.022)	0.041 (0.027)
Custom operators	0.085***[(b)] (0.030)	0.001 (0.020)	-0.086*** (0.025)
Farms' characteristics			
Irrigation system on the farm	-0.041 (0.035)	-0.107*** (0.027)	0.149*** (0.029)
Farms' assets			
Total agricultural expenditure	0.020 [(c)] (0.013)	-0.010 (0.009)	-0.010 (0.010)
Total monetary value of land and buildings	-0.019 (0.013)	-0.014* (0.009)	0.033** (0.013)
Total number of family workers	-0.010 (0.007)	0.012*** (0.004)	-0.002 (0.005)
Total number of non-family workers	-0.008** (0.003)	0.004* (0.002)	003)
Farms' management practices			
Selling the harvest on the farm	0.032 (0.038)	-0.031 (0.022)	-0.001 (0.035)
Selling the harvest to wholesalers	0.021 (0.032)	-0.028 (0.023)	0.007 (0.028)
Selling the harvest to retailers	0.107*** (0.031)	0.008 (0.021)	-0.115*** (0.028)
Selling the harvest to processors	-0.055* (0.031)	-0.017 (0.022)	0.072** (0.029)
Cultivation of high NDV[(d)]	0.212*** (0.026)	-0.110*** (0.014)	-0.102*** (0.023)
Cultivation of medium NDV[(e)]	-0.109*** (0.017)	0.233*** (0.014)	0.124*** (0.013)
Cultivation of low NDV[(f)]	-0.183*** (0.018)	-0.092*** (0.011)	-0.274*** (0.010)
Exogenous factors			
Farm located in Quebec	0.036 (0.086)	0.105* (0.061)	-0.142** (0.057)
Farm located in Ontario	0.194** (0.084)	0.097 (0.063)	-0.291*** (0.057)
Farm located in British Columbia	0.146* (0.089)	0.035 (0.061)	-0.182*** (0.062)
Constant			
Observations	350	350	350
Log Likelihood (full model)	-194.431		
Prob > chi2	0.0000		

Note: (a) NDV means nutrient-demanding vegetables. (b) ***, **, * indicate significance at the 1%, 5%, and 10%, respectively. (c) The semi-elasticities related to logarithmic variables are reported. (d), (e), and (f) represent the Inverse Mill Ratios (IMRs) predicted from the estimations of high, medium and low NDV binary selection, respectively.