Optimal Sustainable Pest and Soil Management for Farmers: A Dynamic Bioeconomic Modeling Framework[1,2]

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Abstract

Organic farming -- wherein farmers do not use synthetic fertilizers, pesticides, herbicides, or fungicides to grow their produce -- is widely considered to be a far more sustainable alternative to conventional food production. In this paper, we review, synthesize, and discuss the economics literature on organic farming; review our research that combines insights from economics and the natural sciences to study and inform farmer transitions from conventional to organic management; and present a framework for dynamic bioeconomic modeling of a farmer's pest and soil management decisions. Our research and framework aims to help farmers improve decision-making around synthetic compound use and organic production, with the ultimate goal of improving soil bacteria stewardship, crop yields, farmer profits, agricultural sustainability, greenhouse gas mitigation, biodiversity, resilience of the organic farming system, the protection of water and other resources, the provision of ecosystem services, and public and environmental health.

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1. Introduction

Conventional farming has been heavily criticized for causing biodiversity loss, soil erosion, and increased water pollution due to the rampant usage of synthetic fertilizers and pesticides. Organic farming -- wherein farmers do not use synthetic fertilizers, pesticides, herbicides, or fungicides to grow their produce -- is widely considered to be a far more sustainable alternative to conventional food production (Varanasi, 2019).

In this paper, we review, synthesize, and discuss the economics literature on organic farming; review our research in Meneses et al. (2024) that combines insights from economics and the natural sciences to study and inform farmer transitions from conventional to organic management; and present a framework for dynamic bioeconomic modeling of a farmer's pest and soil management decisions. Our research and framework aims to help farmers improve decision-making around synthetic compound use and organic production, with the ultimate goal of improving soil bacteria stewardship, crop yields, farmer profits, agricultural sustainability, greenhouse gas mitigation, biodiversity, resilience of the organic farming system, the protection of water and other resources, the provision of ecosystem services, and public and environmental health.

2. The Economics of Organic Farming

Transitioning to organic farming entails the discontinuation of pesticide use, a change that may impact farm profits. The relationship between pesticide use and farm profit has been the subject of many studies. Chambers et al. (2010) shows pesticide use as increasing returns to quasi-fixed factors of production like capital and land. In contrast, Jacquet et al. (2011) use a mathematical programming model to determine whether pesticide use can be reduced without affecting farmer income and find that a up to a 30 percent reduction is possible.

Multiple studies have applied the dynamic optimization and programming toolkits to the study of optimal agricultural management practices. Jaenicke (2000) develops a dynamic data envelopment analysis (DEA) model of crop production to investigate the role soil capital plays in observed productivity growth and the crop rotation effect. Yeh et al. (2024) develop a novel dynamic bioeconomic analysis framework that combines numerical dynamic optimization and dynamic structural econometric estimation, and apply it to analyze the optimal management strategy for Spotted Wing Drosophila, a pest affecting soft-skinned fruits. Wu (2000) develops a dynamic model and solves for the optimal time path for herbicide application. Dynamic models have also been developed to study agricultural productivity (Carroll et al., 2019), agricultural groundwater management (Sears et al., 2019, 2024a, 2024b, 2024c), agricultural disease control (Carroll et al., 2024a), pollination input decisions by apple farmers (Wilcox et al., 2024), supply chain externalities (Carroll et al., 2024b), optimal bamboo forest management (Wu et al., 2024), fisheries management (Conrad et al., 2024; Shin et al., 2024), and grapes (Sambucci et al., 2024).

Delbridge and King (2016) use dynamic programming to address the question of why so few farmers choose to transition to organic farming. They model the decision to transition to organic production as a dynamic programming problem where the transition involves sunk costs, and find the slow uptake of organic farming may be partially driven by the option value generated by the sunk costs associated with organic transition. Other studies have sought to incorporate transition dynamics, such as the empirically documented initial decrease in crop yields associated with conventional to organic transitions, into profitability assessments of organic farming. Dabbert and Madden (1986) find in their multi-year simulation of a 117-hectare crop-livestock farm that the initial decrease in crop yields during an organic transition results in a 30 percentage point decrease in income in the first year of transition. The biological underpinnings of this initial decrease in productivity, and their response to farmer control variables are not made explicit.

3. Adding Insights from the Natural Sciences

Soil microbes benefit agricultural production by enhancing crop nutrient use, stress tolerance, and pest resistance (Lori et al., 2017). New insights from soil science show that the use of synthetic fertilizers and pesticides can be harmful to these beneficial soil microbes (Hussain et al., 2009; Lo, 2010; Kalia et al., 2011, Lori et al., 2017; Blundell et al., 2020). For example, Blundell et al. (2020) find that organic management is associated with decreased pest pressure on tomato plants. This effect is driven by an accumulation of salicylic acid in plant tissue, and is likely mediated by soil microbe communities. Similarly, Lori et al. (2017) find that organic management is associated with increased microbial abundance and activity.

Thus, while using synthetic fertilizers and pesticides may have the initial effect of increasing crop yields, over time these synthetic compounds exert an indirect negative effect on crop yields through their negative effects on soil health. This insight has implications for a farmer's optimal synthetic fertilizer and pesticide strategy, and for whether and how a farmer should transition from conventional to organic farming.

In the long run, pesticide use may even negatively affect profits due to their effects on soil productivity through soil health. Sexton et al. (2007) acknowledge the effect that pesticide use can have on soil health through its impact on soil microbiomes. Kalia and Gosal (2011) also document the damaging effects that the application of pesticides in conventional farming has on soil microorganisms that benefit plant productivity. Jaenicke and Lengnick (1999) estimate a soil-quality index consistent with the notion of technical efficiency. Murphy et al. (2020) find that farmers in developing countries usually do not have sufficient information about their soil nutrient levels to make profit-maximizing decisions about fertilizer usage, and that there can be potentially large net benefits to providing farmers with soil information.

Owing to intertwined feedback links between biological and economic systems, bioeconomic modeling is challenging, and there is a considerable need for studies that couple economic models of decision-making with biophysical models to provide policy-relevant implications (Kling et al., 2017). Stevens (2018) argues that optimal control models may be well suited for studying the economics of soil management. In Meneses et al. (2024), we argue further that dynamic optimization and dynamic programming may help shed light on the optimal rate of transition from conventional to organic farming, by allowing us to better capture the countervailing and dynamic effects that pesticide use has on profits through its effect on pest pressure and soil health.

In our research in Meneses et al. (2024), we develop a dynamic bioeconomic model of a farmer's decisions regarding the use of synthetic compounds (e.g., synthetic fertilizers and pesticides) and the transition from conventional to organic management. Our crop production model accounts for the newly documented interrelationships among synthetic compound use, soil health, and crop yields. We characterize and solve for a "fully informed" farmer's optimal synthetic compound use strategy, and for whether and how a farmer should transition from conventional to organic farming. These solutions are compared to those from a "misinformed" model in which the farmer is not aware of the interactions between synthetic compound use, soil health, and crop yields, allowing us to assess how gaining knowledge of these interactions might be expected to change farmers' synthetic compound use strategies and, ultimately, their decisions around adopting organic management. We identify and discuss agricultural and economic conditions under which farmers can be expected to voluntarily reduce their reliance on synthetic compounds, and possibly even adopt organic management, upon learning of the benefits associated with stewardship of their soil's microbiome. We apply our model to farmer-level pesticide-use panel data to estimate parameters governing farmers' current understanding of the interrelations between soil microbes, pesticides, and crop yields, and to examine possible effects of extension programs targeting farmers' understanding of soil microbes.

4. Dynamic Bioeconomic Modeling Framework

The dynamic optimization problem faced by the farmer is to choose a pesticide and fertilizer input trajectory $c(t)$ to maximize the present discounted value (PDV) of their entire stream of profits from crop production:

$$\max_{\{c(t)\}} \int_0^\infty \left(\left(P_{con} \cdot (1 - I_{org}) + P_{org} \cdot I_{org} \right) \cdot f(c(t), b(t)) - c(t) \right) e^{-\rho t} dt, \tag{1}$$

where P_{con} is the conventional crop price; P_{org} is the organic crop price; I_{org} is a dummy variable that equals 1 if the farm is organic and 0 otherwise; $f(c(t), b(t))$ is the crop production function as a function of pesticide and fertilizer input use $c(t)$ and soil microbes $b(t)$; and ρ is the interest rate.

The choice of the functional form and/or parameter values for the crop production function $f(c(t), b(t))$ is best informed by relevant scientific information from biology, plant sciences, and agronomy. For example, one can calibrate and parameterize the crop production function $f(c(t), b(t))$ with estimates from agronomic and other relevant literatures for the relevant crops. Other model parameters -- including organic crop prices P_{org}, conventional crop prices P_{con}, and the interest rate ρ -- can be calibrated using best available literature estimates, market data, and data and information from stakeholders.

In our research in Meneses et al. (2024), we incorporate newly documented interrelationships among synthetic compound use, soil health, and crop yield from soil science via a biological production for soil microbes $b(t)$ that depends on pesticide and fertilizer input use $c(t)$ as well as the total stock of synthetic compounds in the soil. Our model in Meneses et al. (2024) enables us to analyze the dynamics of soils and pests for better management, and to determine and document the effects of integrating soil and pest management on soil health and fertility, greenhouse gas mitigation, enhanced biodiversity, resilience of the organic farming system, water and other resources, and other ecosystem services.

If the solution to the dynamic optimization problem (1) yields an optimal strategy that differs from farmers' actual decisions, then, to the extent that some of the differences between actual behavior and optimal strategy reflect possible sub-optimal behavior on the part of farmers, the model may suggest ways to improve farmers' soil and pest management. Our research and framework aims to help farmers improve decision-making around synthetic compound use and organic production, with the ultimate goal of improving soil bacteria stewardship, crop yields, farmer profits, and agricultural sustainability.

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