Organic Farming Transitions: A Dynamic Bioeconomic Model

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Selected Poster prepared for presentation at the 2024 Agricultural & Applied Economics Association Annual Meeting, New Orleans, LA: July 28-30, 2024

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Motivation

- Soil microbes can benefit agricultural production by enhancing crop nutrient use, stress tolerance, and pest resistance.
- Use of synthetic fertilizers and pesticides can be harmful to these beneficial soil microbes.
- Therefore, over time these synthetic compounds can exert an indirect negative effect on crop yields through their negative effects on soil health.

Research Objectives

- Characterize a farmer's optimal synthetic compound use strategy over time, given biological interactions
- Examine the feasibility and optimality of organic production
- Assess how knowledge about soil microbiome may affect farmers' decisions about transitioning from conventional to organic management
  - Compare optimal solution under full information to solution when farmer does not have information about soil microbes (farmer misperception)

Dynamic Bioeconomic Model

Modeling approach: Dynamic bioeconomic model of a farmer's decisions regarding synthetic compound use and the adoption of organic management

Stage 1- Conventional Farming.

Stage 2- Organic Farming. Stage 2 is reached if stock of clean soil K(t) reaches organic threshold K_{org}.

State variable $(\boldsymbol{K(t)})$: Stock of clean soil: $K(t) = \bar{C} - C(t)$

Control variable $(\boldsymbol{I(t)})$: Net investment in clean soil: $\dot{K}(t) = I(t) = -\dot{C}(t)$

Optimal control problem:

$$\max_{\{I(t)\}} \int_0^\infty \Big(\big(P_{con} \cdot I\{K(t) < K_{org}\} + P_{org} \cdot I\{K(t) \geq K_{org}\}\big) \cdot f(\cdot) - c(t) \Big) \cdot e^{-\rho t} dt$$

s.t.

$$\dot{K}(t) = I(t) = -\dot{C}(t) \qquad : p(t)$$
$$\dot{C}(t) = c(t) - \mu(X)C(t)$$
$$0 \leq c(t) \leq \bar{c}(K(t))$$
$$0 \leq K(t) \leq \bar{C}$$
$$K(0) \textit{ given}$$

What makes this optimal control problem novel and challenging to solve:
There is a discontinuity at the organic threshold. The partial derivatives near the national organic certification threshold are tricky to calculate, since they involve derivatives of indicator functions.

Full Information vs. Farmer Misperception

Full Information

Crop production function
$y = f(\cdot) = \alpha_b(X)b + \alpha_c(X)c + A_y(X)$

Soil microbe production function
$b = g(\cdot) = \gamma_c(X)c(t) + \frac{1}{2}\gamma_{cc}(X)\big(c(t)\big)^2 + \gamma_K(X)K(t) + A_b(X)$

where: $\gamma_c \leq 0, \gamma_{cc} \leq 0$ (convex costs to synthetic compound use)

Misperception

Crop production function
$\breve{f}(\cdot) = \breve{\theta}(X)c(t) + \breve{\Theta}(X)$

where: $\breve{\theta}(X) \geq 0$, $\breve{\Theta}(X) \geq 0$, and $P_{con} \cdot \breve{\theta}(X) - 1 \geq 0$

Results: Full Information

Optimal Solution Within Each Stage $\boldsymbol{j} \in \{\boldsymbol{con}, \boldsymbol{org}\}$

Direction (Sign) of Net Investment

$R_j(K)$ = rate of return on clean soil capital stock
ρ = rate of return on best alternative investment

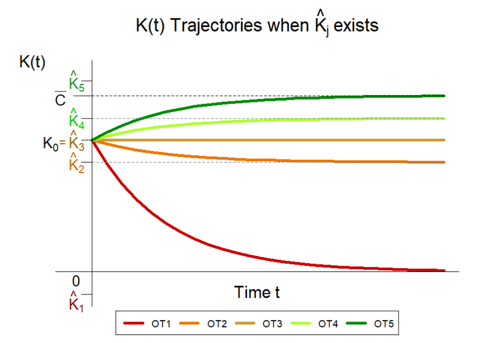
Invest $(I > 0)$ when $R_j(K) > \rho$
Disinvest $(I < 0)$ when $R_j(K) < \rho$
Stay put $(I = 0)$ when $R_j(K) = \rho$ (stationary solution)

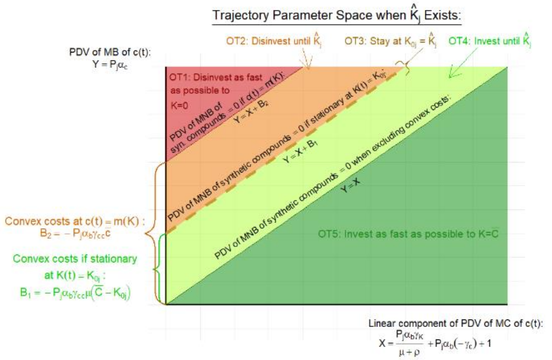
Speed (Magnitude) of (Unconstrained) Net Investment

γ_{cc} introduces nonlinear investment cost
If $\gamma_{cc} = 0$, optimal policy is most rapid approach (MRA)
If $\gamma_{cc} < 0$, then will go more slowly

Intuition from $\boldsymbol{R_j(\hat{K}) = \rho}$

$$\underbrace{P_j \underbrace{\alpha_c}_{\substack{\geq 0 \\ \text{direct effect} \\ \text{of } c(t) \\ \text{on yields}}}}_{\substack{\text{PDV of entire stream} \\ \text{of MB of additional} \\ \text{unit of } c(t) \text{ today}}} = \underbrace{\underbrace{\underbrace{-P_j \underbrace{\alpha_b \left(\underbrace{\gamma_c}_{\substack{\text{linear} \\ \text{effect}}} + \underbrace{\gamma_{cc}\mu\left(\bar{C} - \hat{K}_j\right)}_{\substack{\text{non-lin.} \\ \text{effect}}} \right)}_{\substack{\leq 0 \\ \text{indirect effect of } c(t) \text{ on yields} \\ \text{via its direct neg. effect on soil microbes}}}}_{\substack{\geq 0 \\ \text{indirect MC of additional unit of } c(t) \text{ today} \\ \text{via its direct neg. effect on soil microbes}}} + \underbrace{P_j \frac{\overbrace{\alpha_b\gamma_K}^{\substack{\geq 0 \\ \text{indirect effect} \\ \text{of } K(t) \text{ on yields} \\ \text{via its direct pos.} \\ \text{effect on soil microbes}}}}{\mu + \rho}}_{\substack{\geq 0 \\ \text{PDV of entire stream} \\ \text{of indirect MC of} \\ \text{additional unit of } c(t) \\ \text{today via its indirect} \\ \text{neg. effect on soil} \\ \text{microbes through its neg.} \\ \text{effect on } K(t) \text{ (stock effect)}}}}_{\substack{\text{PDV of entire stream of indirect MC} \\ \text{of additional unit of } c(t) \text{ today via its neg. effects on soil microbes}}} + \underbrace{\underbrace{1}_{\substack{\geq 0 \\ \text{unit price} \\ \text{of } c(t)}}}_{\substack{\text{direct MC of} \\ \text{additional} \\ \text{unit of} \\ c(t) \text{ today}}}}_{\text{PDV of entire stream of MC of additional unit of } c(t) \text{ today}}$$





Results: Full Information (cont.)

Behavior Between Stages

Accidental Organic Transitions

The transition from conventional to organic is "accidental" for either:
1) OT5: Invest as fast as possible until $K = \bar{C}$ by never applying any synthetic compounds, or
2) OT4 if $\hat{K}_{con} \geq K_{org}$: Invest until $\hat{K}_{con}$ by always applying $\hat{c}_j$ at which PDV of MB is 0 since then the optimal solution for a conventional farmer is to continue to invest in the stock of clean soils until he reaches the organic threshold K_{org}

Premium-Induced Organic Transitions

If there is no 'accidental' transition, an organic price premium may still induce some farmers to switch to organic management. Requires the following for some ϵ:

$$\Delta(\epsilon) \equiv V_{org}(K_{org}) - V_{con}(K_{org} - \epsilon) > 0$$

Results: Farmer Misperception

Misperception model only yields solution OT1, such that in the absence of an organic price premium they always want to disinvest as quickly as possible. Therefore, a conventional farmer who does not have knowledge of the role that soil bacteria can play in production will *never* adopt organic farming in the absence of an organic price premium.

Conclusion

When farmers account for soil bacteria: Some may transition to organic management "accidentally" as their optimal trajectories gradually take them toward the certification threshold. This can happen even in absence of an organic price premium.Other transitions may be induced by the organic price premium.

When farmers do not account for soil bacteria:
They never make a gradual transition to organic, and instead disinvest as fast as possible to $K = 0$. If they transition can only be induced by an organic price premium. They will require a higher premium to adopt than a fully informed farmer would when a large enough proportion of organic farming's value-added comes from stock effects/soil microbes.

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Key: $K(t)$- state variable, or clean soil capital stock; $I(t)$- control variable, or net investment in stock of clean soil; $c(t)$- synthetic compound use; $C(t)$- stock of synthetic compounds in soil; $b(t)$- soil microbes; $f(\cdot)$- crop production function; $g(\cdot)$- soil microbe production function; X- other factors of production; μ- rate at which synthetic compounds decay in soil; ρ- interest rate; P_{con}- conventional crop prices; P_{org}- organic crop prices; $K(t) \geq K_{org}$- organic certification requirement; $\bar{C}$- max synthetic compound load that soils can tolerate

Acknowledgements: We received funding from the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA). Gómez, Just, Kanbur, Lee, and Lin Lawell are Faculty Fellows at the Cornell Atkinson Center for Sustainability. All errors are our own.