Organic Farming Transitions: A Dynamic Model

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Organic Farming Transitions: A Dynamic Model

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Introduction

We combine insights from economics and the natural sciences to help farmers improve decision-making around the use of synthetic fertilizers and pesticides, and the adoption of organic management.

New insights from soil science show synthetic agrichemicals can harm soil microbes that benefit farmers by enhancing crop nutrient use, stress tolerance, and pest resistance. Thus, use of synthetic compounds involves short- and long-term tradeoffs.

We develop a dynamic bioeconomic model incorporating feedback effects between synthetic compounds, soil bacteria, and crop yields. Model solution gives farmer's optimal synthetic compound and organic production strategy.

We explore how farmer behavior varies with knowledge of biological feedbacks and changes in parameter values.

Objectives

Objective 1: Determine farmer's optimal synthetic compound use and organic production strategy, given harmful effects of synthetics on soil bacteria, and soil bacteria's benefits for crop yields.

Objective 2: Assess how knowledge of feedback between synthetic compounds, soil bacteria, and yields affects decision to transition to organic management.

Model & Methods

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: $\dot{K}(t) = I(t) = -\dot{C}(t)$

Analysis: We analytically solve the optimization problem for farmer who is aware of soil bacteria, and who is not, in order to assess value of knowledge of feedback between synthetic compounds, soil bacteria, and crop yields.

Optimal control problem:

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

s.t.
$$\dot{K}(t) = I(t) = -\dot{C}(t) \quad : p(t)$$
$$\dot{C}(t) = c(t) - \mu(X)C(t)$$
$$0 \leq c(t) \leq \bar{c}(K(t))$$
$$0 \leq K(t) \leq \bar{C}$$
$$K(0) \text{ given}$$

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.

Model & Methods (cont.)

Full Information

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

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

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

Misperception

Crop production function
$\check{f}(\cdot) = \check{\theta}(X)c(t) + \check{\Theta}(X)$ where: $\check{\theta}(X) \geq 0$, $\check{\Theta}(X) \geq 0$, and $P_{con} \cdot \check{\theta}(X) - 1 \geq 0$

Results: Full Information

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

Direction (Sign) of Net Investment

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

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

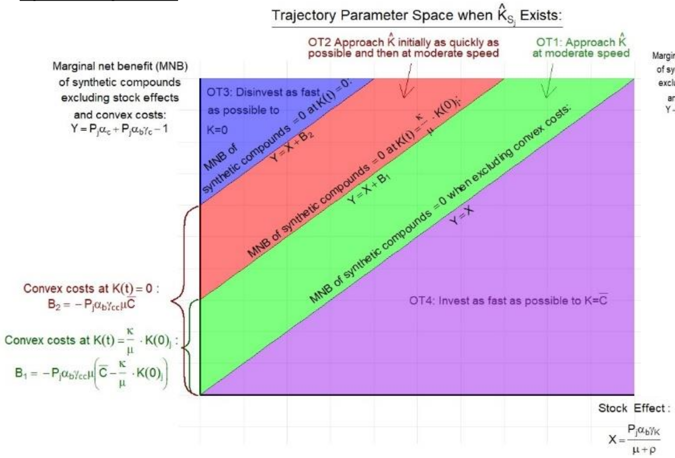
Speed (Magnitude) of (Unconstrained) Net Investment

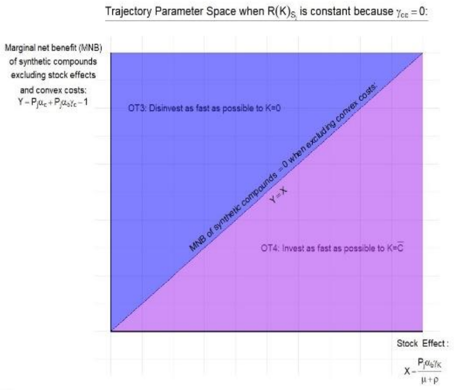
γ_{cc} introduces nonlinear investment cost
If $\gamma_{cc} = 0$, optimal policy is most rapid approach (MRA)
If $\gamma_{cc} < 0$, then will go more slowly

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

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

Optimal Trajectories





OT5: Stay at initial clean soil stock and do not invest or disinvest
1) $\kappa = \mu$ and $\hat{K} \leq K(t)$ (=> always at lower bound of $I(t) = 0$), or
2) $\mu = 0$ (=> $I(t)$ is constrained to be 0)

Results: Full Info (cont.)

Behavior Between Stages

Continuous Organic Transitions in Absence of Organic Price Premium

The transition from conventional to organic is continuous when either:
1) Conventional farmer stationary solution $\hat{K}_{con}$ is above K_{org}, or
2) Conventional farmer stationary rate of return on clean soil stock $R_{con}(K)$ is constant and always greater than ρ

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}

Discrete Organic Transitions

When $\hat{K}_{con} < K_{org}$ or when $R_{con}(K)$ is constant and always less than ρ, there are no continuous transitions from conventional to organic, but the organic price premium may still cause some farmers to "jump" to the organic threshold.

For this to occur we must have 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 OT3, 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.
- Others will have "jump" transitions induced purely 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, will be a "jump" transition & can only be induced by a premium.

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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

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