Agricultural productivity and soil carbon dynamics: 
a bio-economic model

Julia Berazneva*
Charles H. Dyson School of Applied Economics and Management
Cornell University
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Abstract

The strong link between poverty, natural resources and the environment is apparent in smallholder agriculture: farmers are making repeated land use and management decisions while facing diverse resource endowments and significant environmental constraints on production. To investigate the likely effects of changes in agricultural practices on the natural resource base and on farmer welfare, we develop a bio-economic dynamic model of agricultural households in the western Kenya highlands. Our modeling framework extends economic farm household models to incorporate the dynamic nature of natural resource management and its implications for household welfare, and to permit a meaningful interface with biophysical processes through soil carbon management. Using an eight-year panel data set, the model combines econometrically estimated production and soil carbon flow equations in a dynamic programming framework. We use the model to determine the optimal management of the farming system over time in terms of the quantity of mineral fertilizer and crop residues to apply, taking into consideration initial resource endowments and prices. Understanding how soil resources respond to the combined applications of mineral and organic resources is important for improved resource allocation at the farm level and for national agricultural policy decisions.

Keywords: natural resource management, agricultural productivity, bio-economic model, soil carbon dynamics, western Kenya.

*Correspondence to: Julia Berazneva, 438 Warren Hall, Charles H. Dyson School of Applied Economics and Management, Cornell University, Ithaca, NY 14853, USA. E-mail: jb793@cornell.edu.
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Julia Berazneva1, Jon Conrad1 and David Güereña2

1Charles H. Dyson School of Applied Economics and Management, Cornell University and 2Crop and Soil Sciences, Cornell University

Motivation

• Extreme poverty is often associated with environmental degradation (Dasgupta 2010)
• Maize yields in Sub-Saharan Africa have remained stagnant over past 40 years, largely due to depletion of soil fertility (Sanchez 2002)
• Soil fertility constraints require combined applications of chemical fertilizers and organic resources to address crop nutrient demands and agronomic productivity and sustainability goals

Focus on soil carbon

• Strong relation between soil carbon, soil quality, and crop productivity (Lal 2006)
• Land use and management decisions influence the stock of soil carbon (e.g., land conversion to agriculture, residue retention)
• Potential to sequester carbon and offset emissions from fossil fuels

Research goals

A bio-economic model of agricultural households in the Western Kenya Highlands to:
• Study the link between poverty, agricultural production and natural resources
• Analyze soil carbon in a dynamic setting
• Consider initial resource endowment
• Determine optimal application rates of mineral fertilizer and crop residues
• Evaluate the value of soil carbon

Western Kenya Highlands

• Densely populated and poor: 55% of population living below national rural poverty line
• Current practices: maize monoculture, removal of maize residues for fodder and fuel, limited use of hybrid seeds and mineral fertilizers, no following
• Data: agronomic experiment in 2005-2012 household and market surveys in 2011-2013

Economic model

• A farmer cultivates an hectare of land with maize:
  - \( c_t \): stock of soil carbon in year \( t \)
  - \( f_t \): quantity of mineral nitrogen applied in year \( t \)
  - \( \alpha \): share of maize residues left on the field for soil fertility management at the end of year \( t \)
  - \( y_t = y(c_t, f_t, \alpha) \) where \( y(\cdot) \) is a function describing carbon dynamics.
  - \( y_0 \): initial level of soil carbon (given).
  - \( y_{t+1} - y_t = y(c_t, f_t, \alpha) - y_0 - m \)
  - \( m \): depletion of soil fertility

Soil carbon function

\[ y_{t+1} - y_t = y(c_t, f_t, \alpha) - y_0 - m \]

Maize yield function

\[ y_t = y(c_t, f_t, \alpha) \]

Generalized quadratic function of carbon stocks and nitrogen applications:

\[ y_0 = \gamma_0 + \gamma_1 c_0 + \gamma_2 f_0 + \gamma_3 f_1 f_0 + \gamma_4 c_1 f_0 + \gamma_5 c_0 f_1 + \gamma_6 c_0 f_0 + \gamma_7 c_0 \]

\[ y_t = y_0 + \gamma_1 c_t + \gamma_2 f_t + \gamma_3 f_{t-1} \]

\[ y_{t+1} - y_t = \] Net soil carbon change

<table>
<thead>
<tr>
<th>Variable</th>
<th>( \beta = 50 )</th>
<th>( \beta = 100 )</th>
<th>( \beta = 150 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon stock, ( c_0 )</td>
<td>40.45</td>
<td>35.97</td>
<td>20.15</td>
</tr>
<tr>
<td>Maize yield, ( y_0 )</td>
<td>4.19</td>
<td>4.04</td>
<td>3.70</td>
</tr>
<tr>
<td>Nitrogen input, ( f_0 )</td>
<td>0.07</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>Share of residues, ( \alpha )</td>
<td>1</td>
<td>0.86</td>
<td>0.41</td>
</tr>
<tr>
<td>Value of carbon, ( \lambda )</td>
<td>148.23</td>
<td>120.41</td>
<td>107.90</td>
</tr>
</tbody>
</table>

Discounted present value of annual profits, \( \delta = 10\% \): 1. Depleted soils: \( \pi = $1,133 \), 2. Medium-fertility soils: \( \pi = $2,785 \), 3. Fertile soils: \( \pi = $7,332 \)

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