Agronomy and the Economy:
Using soil analysis to understand fertilizer use and effectiveness on smallholder farms in Zambia

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Understanding fertilizer Effectiveness and Adoption in Zambia
Project Overview

- **Collaborators**
  - Team of economists and crop scientists
  - Other support from FSE, GISAIA, IAPRI, ZARI

- **Data**
  - Economic livelihood surveys from 8,800+ households
  - Soil samples & GPS field measurements from 1,600+ “largest maize fields”

- **Challenge – How to use the data**

- **Primary objectives are to understand**
  - Effectiveness (Agronomy) – Estimate response rates ON THE FARM
  - Adoption (Economy) – How does farmer behavior compare to our estimates of profitability
• Motivation and some background
• Agronomic digression
• Framework for “soil data”
• The econometric model (finding thresholds)
• Preliminary results
• A final thought
Outline

- Motivation and some background
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Motivation

• Policy focus = Policy analysis focus

• Fertilizer subsidies were popular during the independence era phased out during Structural Adjustment in the 80’s & 90’s

• Fertilizer subsidy revival during talks of Africa’s Green Revolution

• Plenty of support from many sides - African yields are low
Motivation

• Popular independence era subsidies phased out during Structural Adjustment in the 80’s/90’s

• Fertilizer subsidy revival during talk of Africa’s Green Revolution

• Plenty of support since African yields are so low

• As a matter of fact, nutrients *must* be returned to the soil to intensify farming (reduce fallow)

• No doubt that Africans use very little fertilizer
## Fertilizer use in Africa & the Rest Of the World (2008)

<table>
<thead>
<tr>
<th>Region</th>
<th>Nitrogen total nutrients</th>
<th>Phosphate total nutrients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>48</td>
<td>13</td>
</tr>
<tr>
<td>South America</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>North America</td>
<td>60</td>
<td>18</td>
</tr>
<tr>
<td>Asia</td>
<td>132</td>
<td>47</td>
</tr>
<tr>
<td><strong>Africa</strong></td>
<td><strong>15</strong></td>
<td><strong>4</strong></td>
</tr>
</tbody>
</table>

Source: FAOSTAT
Why don’t African farmers use “enough” fertilizer

- Economically they use exactly enough
- Prevailing assumption = Market limitations
  - Income constraints/high prices
  - Credit
  - Infrastructure – Transport costs
  - Otherwise high transfer costs
- The other side of the coin - How well does it work?

Subsidies
Outline

- Motivation and some background
- *Agronomic digression*
- Framework for “soil data”
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- A final thought
What determines plant growth & yield?

- Climate (temperature, moisture, air quality)
- Soil
- Management (including plant selection)
What in *soil* determines plant growth & yield?

1 – **Available** nutrient stock – the 16 essentials

- **Macronutrients**
  - Nitrogen
  - Phosphorus
  - Potassium
  - Calcium
  - Magnesium
  - Sulphur

- **Micronutrients**
  - Boron
  - Chlorine
  - Copper
  - Iron
  - Manganese
  - Molybdenum
  - Zinc

- **Other nutrients**
  - Hydrogen
  - Carbon
  - Oxygen

- **Non-essentials**
  - Aluminum
  - …more later
Agronomic Digression

- Three potential states that limit plant growth
  - Deficiency – The law of the minimum
“Plants will use essential elements only in proportion to each other, and the element that is in shortest supply—in proportion to the rest—will determine how well the plant uses the other nutrient elements”

-Justus von Liebig, 1862

(actually Karl Sprengel, 1826)
Agronomic Digression

• Three potential states that limit plant growth
  • Deficiency – The law of the minimum
  • Toxicity – too much of a non-essential
  • Imbalance – too much of a good thing (starts crowding out other essentials)

• Note – All these concepts suggest a role of natural thresholds in what determines plant growth (first talked about in Ag. Econ. lit in Marenya and Barrett (2009))
...What in soil determines plant growth?

2 – General soil characteristics

- Soil Chemistry
- Cation Exchange Capacity (CEC)
- Potential Hydrogen (pH) - acidity
P and Maize

Inhibited ability for maize to consume any nutrients (Aluminum toxicity)

Iron and Aluminum Phosphates (less available)

Mono & Dicalcium Phosphates (max available)

Tricalcium Phosphates (less available)

Inhibited ability for maize to consume any nutrients (Aluminum toxicity)

Griffiths (2010); ZARI (2002)
Agronomic Digression

…What in soil determines plant growth?

2 – General soil characteristics

• Soil Chemistry
  • Cation Exchange Capacity (CEC)
  • Potential Hydrogen (pH) – acidity

• Soil Biology
  • Soil Organic Matter (SOM)
Agronomic Digression


![Graph showing marginal value product of applied nitrogen vs. plot carbon content.](image)
...What in soil determines plant growth?

2 – General soil characteristics

• Soil Chemistry
  • Cation Exchange Capacity (CEC)
  • Potential Hydrogen (pH) – acidity

• Soil Biology
  • Soil Organic Matter (SOM)

• Soil Physics
  • Soil texture
Texture triangle
Outline

• Motivation and some background
• Agronomics digression
• Framework for “soil data”
• The econometric model (finding thresholds)
• Preliminary results
• A final thought
Framework for understanding “Soil data”?

Types of Soil Data

- Available Nutrients
  - Macro (e.g., N, P, K)
  - Micro (e.g., B, S, Zn)

- General Characteristics
  - Physics (e.g., Texture)
  - Biology (e.g., SOM)
  - Chemistry (e.g., pH, CEC)

Not best at survey-scale
- Timing is important
- Measurement can be difficult
More common on small samples
Better with plant tissue analysis

Can be reliably measured in the field
Pick one

Can be reliably measured in a lab
Pick one

Changes slowly over time (exogenous)
Outline

• Motivation and some background
• Agronomics digression
• Framework for “soil data”
• The econometric model (finding thresholds)
  • Condensed version for timing?
• Preliminary results
• A final thought
Model – Key variables

- Allow for threshold variation in two ways:
  - Type I (TI) – Thresholds affect yield response to shifting variables (S) only (and maybe yield)

\[ \text{yield} = \beta_1 S + \beta_2 d + \beta_3 S \cdot d + X\gamma \]

where \( d \) is defined as:

\[
\begin{cases} 
  = 0 & \text{if } TI \leq \theta_1 \\
  = 1 & \text{if } TI > \theta_1 
\end{cases}
\]
Model – Key variables

• Allow for threshold variation in two ways:
  • Type II (TII) - Factors affect the entire production function

\[
\text{yield} \begin{cases} 
\beta_{11} S + \beta_{21} d + \beta_{31} S \cdot d + X\gamma_1 & \text{if } TII \leq \theta_2 \\
\beta_{12} S + \beta_{22} d + \beta_{32} S \cdot d + X\gamma_2 & \text{if } TII > \theta_2
\end{cases}
\]
Many models

- TI – SOM, texture - Soil biology/physics
- TII – pH, CEC – Soil chemistry
- 4 models – Yield response will be a function of:
  - SOM & pH
  - SOM & CEC
  - Texture & pH
  - Texture & CEC
- Response conditional on timing of application and quadratic term in each model
Model – Control variables

• In addition to soil variables and fertilization the model controls for:
  • Seed rate (quadratic)
  • Plant variety
  • Timing of planting
  • Tillage method
  • Education (proxy)
  • Land/family labor ratio – Hired labor dummy
  • Other factors that do not seem to affect results (liming, irrigation, weeding, agroforestry, crop mixing, insecticide and herbicide use, manure and compost, flooding and flood prevention...)

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Outline

• Motivation and some background
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Maize yield response (kg/kg) to inorganic fertilizer (2012)

<table>
<thead>
<tr>
<th>Soil Organic Matter</th>
<th>pH level</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low &lt;=5.4</td>
<td>High &gt;5.4</td>
</tr>
<tr>
<td>Low</td>
<td>2.22***</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>(n=107)</td>
<td>(n=495)</td>
</tr>
<tr>
<td>Threshold</td>
<td>1.2%</td>
<td>1.4%</td>
</tr>
<tr>
<td>High</td>
<td>4.47***</td>
<td>3.90***</td>
</tr>
<tr>
<td></td>
<td>(n=91)</td>
<td>(n=294)</td>
</tr>
</tbody>
</table>

- Thresholds about where one would expect
- Substantial effect from SOM
Impact of SOM on response rate

Average Product of Fertilizer (kg/kg) vs Soil Organic Matter (%)

- Full sample
- High pH
- Low pH
Maize yield response (kg/kg) to inorganic fertilizer (2012)

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- Thresholds about where one would expect
- Substantial effect from SOM
- BUT – higher mean effect on acid soils?!
Productivity on acid soils???-part 1

Lowess smoother

Average product of fertilizer vs. pH as measured by Calcium Chloride

bandwidth = .2
Lowess smoother

Average product of fertilizer vs. pH as measured by Calcium Chloride

bandwidth = .4
TI = texture; TII = pH (M2)
Zambian textures

- Clay Separate: 4.6%
- Clay: 1.2%
- Silty Clay: 1.3%
- Clay Loam: 2.4%
- Silty Clay Loam: 1.3%
- Loam: 0.1%
- Silt Loam: 2.1%
- Silt: 0.4%
- Sand: 16.1%
- Sandy Clay: 46.7%
- Sandy Clay Loam: 1.0%
- Sandy Loam: 22.9%
- Loamy Sand: 0.4%

Sand Separate, %
Texture groups by clay

- Clay separate, %
- Silt separate, %
- Sand separate, %

- Clay
- Silty clay
- Sandy clay
- Clay loam
- Silty clay loam
- Sandy clay loam
- Loam
- Sandy loam
- Silt loam
- Silt
- Sand
- Loamy sand

17%
25%
51%
7%
TI=texture; TII=pH (M2)

Maize yield response (kg/kg) to inorganic fertilizer (2012)

<table>
<thead>
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<th>High &gt;5.6</th>
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<tr>
<td>Less clay - 1</td>
<td>1.86***</td>
<td>1.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n=86)</td>
<td>(n=33)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3.55***</td>
<td>2.63***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n=209)</td>
<td>(n=64)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.60***</td>
<td>4.08***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n=380)</td>
<td>(n=150)</td>
<td></td>
</tr>
<tr>
<td>More clay - 4</td>
<td>3.54***</td>
<td>4.16**</td>
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<td>(n=40)</td>
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- Texture effects about what one would expect
Average product of fertilizer (Full Sample)

Graphs by tx2
Average product of fertilizer (High pH Sample)

Less Clay

More Clay

Graphs by tx2
TI=texture; TII=pH (M2)

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• Texture effects about what one would expect

• BUT – higher mean effect on acid soils… again?!
Productivity on acid soils???-part 2

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Average product of fertilizer vs pH as measured by Calcium Chloride

bandwidth = .2
Productivity on acid soils??-part 2

Lowess smoother

Average product of fertilizer

pH as measured by Calcium Chloride

bandwidth = .4
Economic implications

• Again – Nutrients need to be returned

• “On the farm” response rates to currently promoted fertilizers appear insufficient to provide economic incentive for many
  • 49 – 77% of users have estimated response below 4.1

• Estimated response rates at recommended application for non-users suggest profitable returns if applied “on time”.
  • 73-77% of non-users have estimated response above 4.1
Other options

- Management
  - Lime (pH, Deficiencies)
  - Manure (SOM, pH)
- Extension
  - Training
  - Demonstration plots
- R & D – Seeds, fertilizer mixes, organic options
- Diversifying diets - grow crops more appropriate for soils/ ecology/human nutrition)
  - Attachment to maize as “traditional” foods is a myth!
  - E.g. maize is not a “traditional” African food
- Rotating/Intercropping N-fixing legumes
- Agro-forestry
- Integrated approach – “Conservation agriculture”
A final thought on fertilizer subsidies in Africa

- Malawi and Zambia started out in very different places: Emergency relief is not a long term plan.

- Whether or not current response rates are profitable, they could be MUCH improved – Let’s focus on that!

- Is there a “simple” solution to increasing productivity (e.g. uniform fertilizer subsidies)
Constraints for African Agriculture

Constraints for African Agriculture

Constraints for African Agriculture

Constraints for African Agriculture

Constraints for African Agriculture

Constraints for African Agriculture

Constraints for African Agriculture

Constraints for African Agriculture

Thank You!

Email: burkewi2@stanford.edu
Two types of threshold
- TI - only affects fertilizer
- TII - affects entire production function

4 models - Yield response will be a function of:
- SOM & pH
- SOM & CEC
- Texture & pH
- Texture & CEC

Response conditional on timing of application and quadratic term in each model

Controlling for other inputs, labor, unobservable variables, etc.

**Carry on**