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Introducing a new non-monotonic economic measure of soil quality

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ABSTRACT

Agricultural production relies on soils. Even though many indicators of soil quality have been proposed, a unique consensus on the best indicator is not reached. This contribution proposes a methodology to aggregate quantitative soil characteristics through the use of economic theory. This aggregation method, which is general and can be applied to any production context, yields a soil-quality measure that summarizes soil characteristics in output terms, among Kenyan maize (*Zea mays* L.) farmers situated on different types of soils (FAO, 2015). Our methodology, developed at the University of Maryland in 2011, uses simple linear programming to obtain a measure of soil quality. We hypothesize that carbon and clay might have negative marginal effects on soil quality. Our results confirm this hypothesis by demonstrating that soil carbon has a negative impact on soil quality for concentrations above 40 g kg^{-1}, depending on clay concentration.

1. Introduction

Even though soil quality is a particularly critical factor in plant production, no commonly agreed measure of soil quality exists. Lacking proper soil-quality measures, a number of studies have attempted to examine the role of soil quality in production via less direct methods. For example, a series of studies have assessed the role of soil quality through the use of qualitative variables, such as slope, soil color, soil type, and soil depth (Sherlund et al., 2002; Abdulai and Binder, 2006; Di Falco and Chavas, 2009; Fuwa et al., 2007; Bellon and Taylor, 1993; Chang and Wen, 2011). Some studies (Marenya and Barrett, 2009a,b; Barrett et al., 2010) have included quantitative soil characteristics, such as soil carbon, in a regression setting. Others have considered quantitative soil characteristic inputs as freely disposable[2] to create a soil-quality index, by using nonparametric linear programs that exploit radial (Jaenicke and Lengnick, 1999) or non-radial (Hailu and Chambers, 2012) aggregation methods. We propose our method by exploiting radial methods. Jaenicke and Lengnick (1999) obtain a soil-quality index multiplicatively separable from other non-aggregated factors.[3] In the context of measuring Swedish pharmacy quality, Färe et al. (1995) first define an intertemporal quality index without exploiting separability and then use multiplicative separability to derive a quality index only as a function of quality attributes.

In soil science, usual approaches (Andrews et al., 2002) to construct soil-quality indexes follow parametric functions to transform physical, chemical, and biological soil-quality variables into scores and then use simple weighted averages to aggregate these scores into soil-quality indexes. The soil variables scoring methods are usually monotonically increasing, unidimensional, and do not account for potential interactions among soil characteristics. Some authors (e.g. Andrews et al., 2004) have used predetermined (parametric) expected curve shapes (scoring curves) and directions of change (more is better, less is better, mid-point optima) to obtain scores related to single soil characteristics, which include, in some instances, potential negative effects and interactions among single soil characteristics. These scores are then usually aggregated in one measure with fixed weights. Other proposals to measure soil quality include the development of indexes, such as the whole soil stability index (Nichols and Toro, 2011), or the usage of principal component analysis to aggregate soil-quality characteristics (Li et al., 2013). In their review, Bastida et al. (2008) consider the available soil-quality indexes as well as the parameters composing them. Of specific interest to this article are the multiparametric quality indexes based on mathematical-statistics methods. One of the avenues for future soil-quality indicators identified in Bastida et al. (2008) is the usage of infrared spectroscopy to collect data, similar to the ones exploited in this article. This avenue is pursued, for example, in Kinoshita et al. (2012), where near-infrared reflectance spectroscopy data are

[1] The work has been developed at the University of Maryland College Park, now the author works at the European Commission Joint Research Centre.

[2] This concept is equivalent to assuming that soil characteristics can be disposed without incurring costs.

[3] The concept of multiplicative separability amounts to the possibility of separating a function in two factors. A multiplication between the two aggregates obtains again the original function. A multiplicatively separable function A can be decomposed in two components $A(b, h) = D(b)F(h)$, given two functions D and F.

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aggregated in composite soil-quality indexes using parametric scoring functions.

Even if some scientists (e.g. Andrews et al., 2004) recognize that the impacts of soil characteristics on soil quality can be negative, these impacts are restricted to predetermined parametric curve shapes and directions of change. Present approaches in production economics do not use explicitly separability theory, nor do they recognize that the impact might depend on the level of other variables and be negative. Therefore, it is necessary to broaden production economics' methods to appropriately incorporate soil quantitatively into agricultural production analysis.

We use the strengths from the production economics' literature (nonparametric separable flexible aggregation methods) and from soil science (recognition of interaction among soil characteristics and potentially negative effects on soil quality) to propose a nonparametric economic methodology to aggregate production factors[4] through the use of separability theory (Blackorby et al., 1978). As an exemplifying case study, this methodology is applied to create a soil-quality measure by aggregating quantitative soil characteristics from maize (*Zea mays* L.) plots of Kenyan farmers. This measure quantifies economically soil characteristics in output terms. It is a comparative measure of soil quality, in terms of produced outputs, similar to the concept of bonitation (Karmanov, 1980), which is a quantitative soil fertility indicator.

The notion of separability used in this contribution is weaker than previously used in applications to soil. This weak notion of separability allows non-monotonic effects of aggregated soil characteristics on the soil-quality measure. Our methodology hypothesizes that carbon and clay might have negative marginal effects on soil quality. If negative effects exist, we are interested to understand at what concentrations of carbon and clay these effects appear. In this contribution, we show that these detrimental effects to soil quality and to maize output are clearly present for soil carbon and depend on the concentrations of soil clay. Even though there is no universal soil-quality measure that identifies unique optimal soil characteristics ranges, some soil scientists (e.g. Loveland and Webb, 2003; Patrick et al., 2013) agree in identifying best soil quality in correspondence of carbon concentrations between 20 g kg^{-1} and 44 g kg^{-1}, depending on soil clay concentration.

2. Methods

We represent the multiple outputs by $\mathbf{y} \in \mathbb{R}_+^S$ and $\mathbf{x} \in \mathbb{R}_+^U$ denotes a vector of inputs controlled by the producer. Land area is denoted by $l \in \mathbb{R}_+$ and soil-quality characteristics are denoted by $\mathbf{c} \in \mathbb{R}_+^Q$. The technology is described by $T \subset \mathbb{R}_+^U \times \mathbb{R}_+ \times \mathbb{R}_+^Q \times \mathbb{R}_+^S$:

$$T = \{(\mathbf{x}, l, \mathbf{c}, \mathbf{y}) \in \mathbb{R}_+^{U+1+Q+S} : (\mathbf{x}, l, \mathbf{c}) \text{ can be used to produce } \mathbf{y}\}. \quad (1)$$

The technology T includes all convex combinations of given input and output observations; it assumes that only finite output can be obtained from finite inputs (boundedness of output set which is also assumed closed); outputs $\mathbf{y}$ and inputs ($\mathbf{x}$, l) can be disposed without incurring costs (strong disposability); finally, the technology T includes only convex combinations of soil characteristics $\mathbf{c}$ (convexity of the input requirement set of soil characteristics).

To represent the technology, we use an output oriented Farrell measure (Farrell, 1957), which is a measure of distance between potential and observed output given the same inputs:

$$E(\mathbf{x}, l, \mathbf{c}, \mathbf{y}) = \max \{e \in \mathbb{R}_+ : (\mathbf{x}, l, \mathbf{c}, e\mathbf{y}) \in T\} \quad (2)$$

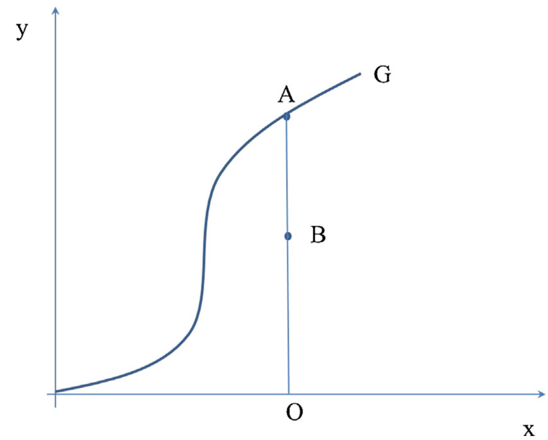

Fig. 1. Farrell output efficiency measure.

if $\exists\ e$ s.t. $(\mathbf{x}, l, \mathbf{c}, e\mathbf{y}) \in T$ and 0 otherwise, and where $E : \mathbb{R}_+^{U+1+Q+S} \to \mathbb{R}_+$. By strong disposability of outputs

$$E(\mathbf{x}, l, \mathbf{c}, \mathbf{y}) \geq 1 \Leftrightarrow (\mathbf{x}, l, \mathbf{c}, \mathbf{y}) \in T \quad (3)$$

so that $E(\mathbf{x}, l, \mathbf{c}, \mathbf{y})$ is a complete function representation of the technology. If we consider the graph G of a simplified technology composed of one input (x) and one output (y) in Fig. 1, the measure of Farrell output efficiency (e) is the ratio between potential output (OA in the figure) and realized output (OB in the same figure).

2.1. Using separability to create an aggregate soil-quality measure

To create a measure of soil quality, we impose a separable structure upon $E(\mathbf{x}, l, \mathbf{c}, \mathbf{y})$. Specifically, we assume $\mathbf{c}$ are separable from $\mathbf{x}$, l, $\mathbf{y}$:

$$E^s(\mathbf{x}, l, g(\mathbf{c}), \mathbf{y}) = E(\mathbf{x}, l, \mathbf{c}, \mathbf{y}) \quad (4)$$

where $E^s : \mathbb{R}_+^{U+2+S} \to \mathbb{R}_+$ and $g : \mathbb{R}_+^Q \to \mathbb{R}_+$. $g(\mathbf{c})$ is interpretable as an aggregate of multiple soil-quality characteristics.

Our approach to measuring $g(\mathbf{c})$ is to adapt a fundamental result in separability theory (Theorem 3.2a and Corollary 3.2.0a of Blackorby et al., 1978) that demonstrates one can obtain an ordinal representation of $g(\mathbf{c})$ from the image of $E(\mathbf{x}, l, \mathbf{c}, \mathbf{y})$ through the use of reference levels of $\mathbf{x}$, l, and $\mathbf{y}$ as follows. If the structure is truly separable, then for arbitrary reference levels $\bar{\mathbf{x}}, \bar{l}, \bar{\mathbf{y}}$:

$$E^s(\bar{\mathbf{x}}, \bar{l}, g(\mathbf{c}), \bar{\mathbf{y}}) = E(\bar{\mathbf{x}}, \bar{l}, \mathbf{c}, \bar{\mathbf{y}}) \quad (5)$$

which can be rewritten as[5]

$$m(g(\mathbf{c})) := E(\bar{\mathbf{x}}, \bar{l}, \mathbf{c}, \bar{\mathbf{y}}) \quad (6)$$

so that we can recognize $E(\bar{\mathbf{x}}, \bar{l}, \mathbf{c}, \bar{\mathbf{y}})$ as an ordinal soil-quality measure. Our aggregate $m(g(\mathbf{c}))$ quantifies, in output terms, the product of given soil characteristics for specific reference levels of other inputs and outputs. If the technology is truly separable, the change in reference levels only shifts the value of the measure but not its ordering.

This measure is different from the measures in Jaenicke and Lengnick (1999) and Färe et al. (1995). Our aggregate measure is equivalent to theirs if the same assumptions are done on the possibility of disposing inputs and if the technology is homothetic

[4] In particular, we consider the case of aggregating inputs, but outputs could be aggregated similarly.

[5] My thanks for showing me the possibility of writing this go to Professor Dr. Robert G. Chambers. More details on the empirical model can be found at http://drum.lib.umd.edu/handle/1903/16962.