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A Framework for Evaluating the Sustainability and Economic Viability of Crop–Livestock Systems in Sub-Saharan Africa

Abstract: Improved crop–livestock production systems and technologies are currently being developed in sub-Saharan Africa in response to the growing demand for food and the degradation of the natural resource base. These technologies must not only enhance food production, but they also need to maintain ecological stability and preserve the natural resource base, that is, they must be sustainable. However, the notion of sustainability has been of limited operational use to policy-makers and researchers attempting to evaluate new technologies and/or determine the effects of various policies and technologies. This paper discusses a methodology for measuring the sustainability and economic viability of crop–livestock systems. The approach is based on the concept of intertemporal and interspatial total factor productivity, paying particular attention to the valuation of natural resource stock and flows. The method is applied to a data set available at the International Livestock Centre for Africa. Intertemporal and interspatial total factor productivity indexes are computed for three farming systems in southwestern Nigeria. Results show that the sustainability and economic viability measures are sensitive to changes in the stock and flow of soil nutrients as well as material inputs and outputs. The advantage of this approach is that intertemporal and interspatial total factor productivity measures are computed using only price and quantity data, thus eliminating the need for econometric estimation.

INTRODUCTION

Livestock are an important component of farming systems in sub-Saharan Africa. They are raised mainly for meat, milk and skin, and provide a flexible financial reserve for farmers in years of crop failure. They also play a critical role in the agricultural intensification process by providing draught power and manure for fertilizer and fuel (Winrock, 1992; and Fitzhugh *et al.*, 1992). With increasing human population and economic changes, cultivated areas in many sub-Saharan African countries have expanded onto marginal lands and fallow periods are being shortened. As a result large areas of land are degrading and crop and animal yields are falling (IBRD, 1989; and Ehui and Hertel, 1992). It has been shown that where both crops and livestock are raised, technology is low, inputs scarce, and markets poorly developed, population pressures lead to the evolution of crop–livestock systems as the most efficient and sustainable means of increasing production from a fixed land base (McIntire *et al.*, 1992). Thus small holders will benefit from livestock if they can be successfully integrated with the cropping systems.

Improved crop–livestock production systems and technologies are currently being developed in response to the growing demand for food and the degradation of the natural resource base (ILCA, 1992). These technologies must not only enhance food production but also maintain ecological stability and preserve the natural resource base, that is, they must be sustainable. However the notion of sustainability has been of limited operational use to policy-makers and researchers attempting to evaluate new technologies and/or determine the effects of various policies and technologies. This paper discusses a

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methodology for measuring the agricultural sustainability and economic viability of crop–livestock systems. The approach is based on the concept of intertemporal and interspatial total factor productivity (TFP), paying particular attention to valuation natural resource stock and flows (Ehui and Spencer, 1993).

The next section presents the model. Intertemporal and interspatial TFP indexes which are used to measure the sustainability and economic viability of production systems are derived. The third section presents data sources and construction. The empirical results are reported in the fourth section and the paper closes with some concluding comments.

DERIVATION OF INTERTEMPORAL AND INTERSPATIAL TFP INDEXES

The conventional approach to growth accounting uses TFP indexes to measure the residual growth in outputs not accounted for by the growth in factor inputs. The rate of growth of TFP is conventionally defined as the rate of growth of aggregate output minus the rate of growth of aggregate inputs (Capalbo and Antle, 1988).

Agriculture, however, is a sector which utilizes common pools of natural resources (e.g., air, water, soil nutrients etc.). The stock of these resources affects the production environment, but is in many cases beyond the control of the farmers. For example, soil nutrients are removed by crops, erosion or leaching beyond the crop root zone, or other processes such as volatilization of nitrogen. Agricultural production can also contribute to the stock of some of the nutrients, particularly of nitrogen by leguminous plants and animal manure.

When the stock of nutrients is reduced through nutrient losses, the farmer faces an implicit cost in terms of productivity loss. Conversely when the stock of resource is increased during the production process (e.g., via nitrogen fixation or manuring) the farmer derives an implicit benefit from the system. If these implicit costs and benefits are not accounted for when TFP is measured, results will be misleading.

The model used here builds on that developed recently by Ehui and Spencer (1993). They show that a system can be said to be sustainable if the associated intertemporal TFP index, which incorporates and values changes in the resource stock and flow, does not decrease. They also show that a system can be said to be economically more viable than another one if the interspatial TFP index associated with the former (which incorporates and values spatial differences in the resource stock and flow), is higher than the interspatial TFP index associated with the latter. While intertemporal TFP is about the productive capacity of a system over time (thus sustainability) interspatial TFP is a static concept which refers to the efficiency with which with which resources are employed in the production process at a given period. In both cases the measures include the unpriced contribution from natural resources and their unpriced production flows.

Figure 1 illustrates the difference between intertemporal and interspatial TFP for two hypothetical systems. System 1 is sustainable since its intertemporal TFP increases from a to d over the same period. On the other hand, System 2 is economically more viable (or efficient) than System 1 in year 2 (c is greater than a), but it is economically less viable in year n (d > b).

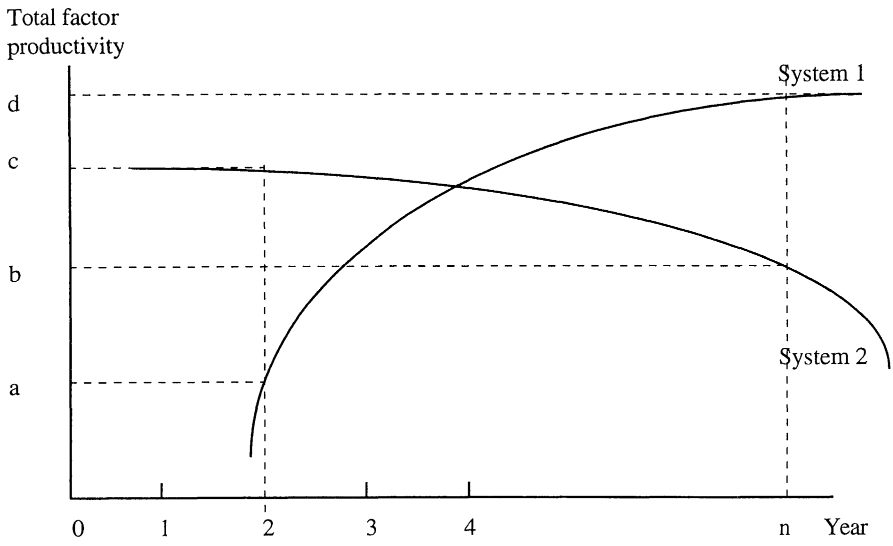

Figure 1 *Total Factor Productivity Changes for Two Hypothetical Agricultural Systems Over Time*

To derive the generalized model for TFP measurement, Ehui and Spencer (1993), solve a maximization problem. When changes in resource stock levels are positive, the problem is stated as:

$$\underset{[Y_t, Z_t]}{\text{Max}\pi_t} = P_{yt}Y_t + P_{zt}Z_t - G(Y_t, Z_t, W_t, B_t, t) \tag{1}$$

where π_t is a measure of aggregate profit in period t, including all benefits and costs of resource exploitation; Y_t is an index of crop outputs; Z_t is an externality denoting the net resource flow in period t, (when changes in resource abundance levels are positive, we have a positive externality and the resulting net resource flow); Z_t is treated as an output, thus contributing positively to the aggregate profit. P_{yt} and P_{zt} are the product and resource flow prices; B_t is a technology shift variable representing the level of resource abundance in period t. Equation (1) represents the case of 'open access' in which B_t is not a choice variable. The resource stock is beyond the control of farmers who thus ignore its opportunity cost. $G(\cdot)$ is the variable cost function for the optimal combination of variable inputs, where $\partial G(\cdot)/\partial B < 0$ and $\partial G(\cdot)/\partial Z > 0$. W_t is a vector of variable input prices; t, is the time trend representing the state of technical knowledge.

When the production process is depleting the resource at a rate faster than that required for sustainability, net changes in resource abundance levels are negative. Thus, we have a negative externality and Z_t is treated as a cost, contributing negatively to the aggregate profit. This requires modification of the objective function, Equation (1,) by replacing the (+) sign before $P_{zt}Z_t$ with a (–) sign, and in this case, $\partial G(\cdot)/\partial Z < 0$.

Using the first-order conditions of Equation (1), development of the continuous time Divisia index by the method of the growth accounting approach gives:

$$(2)\quad -\partial LnC/\partial t = [(P_y Y)/C]\dot{Y} + [(P_z Z)/C]\dot{Z} - \Sigma_j [(W_j X_j)/C]\dot{X}_j - \dot{B}$$

where, $C = \Sigma_j W_j X_j + P_y Y + P_z Z =$ total revenue, assuming constant returns to scale. Dots on variables imply the logarithm derivation of the associated variable with time.

When changes in the resource stock are negative, the productivity index becomes:

$$(3)\quad -\partial LnC/\partial t = [(P_y Y)/C]\dot{Y} - [(P_z Z)/C]\dot{Z} - \Sigma_j [(W_j X_j)/C]\dot{X}_j - \dot{B}$$

where $C = \Sigma_j W_j X_j + P_z Z = P_y Y$, assuming constant returns to scale.

Equations (2) and (3) indicate that TFP is measured as the residual after the growth rate of output $\{[P_y Y/C]\dot{Y}\}$ has been allocated among changes in inputs $\{\Sigma_j[(W_j X_j)/C]\dot{X}_j\}$ and resource abundance $\{\dot{B}\}$ and flows $[(P_z Z)/C]\dot{Z}$. The basic difference between Equations (2) and (3) is that in the former case the change in resource stock is assumed positive and the resulting flow is treated as a benefit. In the latter case, the change in resource stock is assumed to be negative and the resulting flow is treated as a cost.

It is clear from Equations (2) and (3) that total factor productivity measures are biased unless account is taken of variations in the resource stock abundance levels and resource flows. Note that although it is not a choice variable, B_t is part of the solution because it appears in the variable cost function, G.

A discrete-time approximation to the continuous time Divisia indexes of Equations (2) and (3) is given by the Tornqvist approximation (Diewert, 1976; and Ehui and Spencer, 1993). Allowing for resource abundance and flows, this approximation gives measures of the intertemporal and interspatial TFP indexes. As in Equations (2) and (3) we distinguish between two cases:

Case 1: Case of Net Positive Changes in Resource Stock

– intertemporal TFP

$$(4)\quad \tau_{st} = \tfrac{1}{2}\Sigma_j[R_{js} + R_{jt}].[LnY_{js} - LnY_{jt}] + \tfrac{1}{2}[R_{zs} + R_{zt}].[LnZ_s - LnZ_t]$$
$$-\tfrac{1}{2}\Sigma_k[S_{ks} + S_{kt}].[LnX_{ks} - LnX_{kt}] - [LnB_s - LnB_t]$$

– interspatial TFP

$$(5)\quad \rho_{io} = \tfrac{1}{2}\Sigma_j[R_{ji} + R_{jo}].[LnY_{ji} - LnY_{jo}] + \tfrac{1}{2}[R_{zi} + R_{zo}].[LnZ_i - LnZ_o]$$
$$-\tfrac{1}{2}\Sigma_k[S_{ki} + S_{ko}].[LnX_{ki} - LnX_{ko}] - [LnB_i - LnB_o]$$

Case 2: Case of Net Negative Changes in Resource Stock

– intertemporal TFP

(6) $$\tau'_{st} = \Sigma_j [LnY_{js} - LnY_{jt}] - \tfrac{1}{2}[S_{zs} + S_{zt}].[LnZ_s - LnZ_t] - \tfrac{1}{2}\Sigma_k [S_{ks} + S_{kt}].[LnX_{ks} - LnX_{kt}] - [LnB_s - LnB_t]$$

– interspatial TFP

(7) $$\rho'_{io} = \Sigma_j [LnY_{ji} - LnY_{jo}] - \tfrac{1}{2}[S_{zi} + S_{zo}].[LnZ_i - LnZ_o] - \tfrac{1}{2}\Sigma_k [S_{ki} + S_{ko}].[LnX_{ki} - LnX_{ko}] - [LnB_i - LnB_o]$$

In Equations (4)–(7) s and t represent two distinct time periods and i and o represent two distinct farming systems or two distinct geographical areas; B is the composite index of soil nutrient abundance; Z denotes the resource flow; $R_j = (P_j Y_j)/(\Sigma_j P_j Y_j)$ is the revenue share for output Y_j; $S = (W_k X_k)/(\Sigma_k W_k X_k)$ is the cost share for variable input k, and S_z and R_z are the cost and revenue shares of resource flow Z. The basic difference between τ_{st} and ρ_{io} and τ'_{π} and ρ'_{io} is that in Equations (4) and (5) the net increase in resource stock is treated as benefit while in Equations (6) and (7) it is treated as cost. It is clear from Equations (4)–(7) that the productivity differences across different farming systems and time periods can be broken into four components including: (a) an output effect (the first term in Equations (4)–(7), (b) a resource flow effect (the second term in Equations (4)–(7) effect, (c) an input effect (the third term in Equations (4)–(7) and (d) a resource stock effect (the last term in Equations (4)–(7)).

DATA SOURCES

The framework discussed above is demonstrated using a set of data generated during a nine-year study by the International Livestock Centre for Africa (ILCA) at one of its West African research sites in Ibadan (Southwestern Nigeria). The experiment comprised of three systems: (a) the traditional method of cultivation (System A), commonly known as bush fallow system; (b) the continuous alley farming systems (System B); and (c) alley farming with fallow (System C).

In the traditional system farmers fell and burn the fallow vegetation, cultivate the cleared land (typically one to three years) and then abandon the site (from four to twenty years) to forest or bush cover (Sanchez, 1976). This traditional agricultural production system, which is known to be stable and biologically efficient, operates effectively only where there is sufficient land to allow a long fallow period to restore soil productivity (Kang *et al.*, 1989). The fallow land also serves as a source of feed for the animals. In recent times, population growth and various economic changes have caused the fallow period to be shortened or eliminated. This is resulting in increased degradation of farm land, lower supply of quality feed, declining crop and animal yields, and reduced production of food from both crop and animal origins.

Alley farming is an agroforestry system in which crops are grown in alleys formed by hedgerows of trees and shrubs, preferably fast-growing leguminous species. The hedgerows are cut back at the time of planting of food crops and are periodically pruned during cropping to prevent shading and to reduce competition with the associated food crops. They may also be established along the slope to minimize erosion. A portion of the hedgerows' foliage is used as animal feed. Use of the woody legumes provides rich mulch and green manure to maintain soil fertility, enhance crop production, and provide protein-rich fodder for livestock. In the case of this experiment, small ruminants were part of the system and fed with part of the hedgerow foliage. One major advantage of alley farming over the traditional bush fallow system is that cropping, animal feeding and fallow phases can take place concurrently on the same land unit, allowing the farmer to crop the land and feed his/her animals for an extended period. However where it is technically feasible, it is possible to combine alley farming with some short cycle fallow periods as in System C.

Since the cropping systems have multiple crop outputs (maize and cowpea) an implicit output index is calculated by dividing the total value of all output by a price index. The latter is obtained by weighting the maize and cowpea prices by the revenue share of each crop.

Three major inputs are distinguished: planting materials, labour and fertilizer. While labour and fertilizer input quantities are used as observed, the planting material indexes are bilateral Tornqvist chain indexes for each type of planting materials. Planting materials for each crop are aggregated into a single index weighted by the cost share of each planting material.

The Divisia index for the soil nutrient stock is calculated by share-weighting the total quantities of main soil nutrients (nitrogen, phosphorous and potassium) available in the top soil (0–10cm). The opportunity cost of each soil nutrient is approximated by its replacement cost, that is, market price for chemical fertilizer. Resource (nutrient) flows are derived as the difference between nutrient abundance levels for a given production system between 1983 and 1984, and between 1983 and 1990. We chose these two periods to assess short-run and long-run effects.

EMPIRICAL RESULTS

Intertemporal and interspatial total factor productivity indexes for the three production systems under different scenarios were calculated and are reported in Tables 1 and 2, respectively. The basic analysis is conducted under two scenarios: (a) with and without resource stock and flows and (b) with and without a livestock component. Scenario (b) was evaluated in order to assess the impact of the livestock component on the TFP measures.

From column (5) in Table 1, over the period from 1983 to 1990, total factor productivity increased for the continuous alley farming systems (System B) and declined for both the traditional system (System A) and alley farming with fallow (System C). The continuous alley farming system produces 1.28 times as much output in 1990 as in 1983 using the 1983 input bundle. The continuous alley farming system can be said to be sustainable over the seven-year interval because, after properly accounting for temporal differences in input quality and quantity and resource flows and stocks, it produced more than in the reference year (1983). The traditional bush fallow system and the alley farming systems with fallow produced only 0.78 and 0.60 as much output in 1990 as in 1983 using the 1983 input bundle. Thus these two systems can be said to be non-sustainable. During the period 1983–84, the three systems had total factor productivity measures greater than one, indicating that they were sustainable over the relatively short one-year period (Table 1, column 3). Note from Table 1 that totally accounting for changes in resource stock levels and flows alters the productivity measures. For example, during 1983–90 when resource stock and flows are not accounted for, results indicate that the continuous alley farming system and the traditional bush fallow system produced 1.46 and 0.92 (Table 1, column 2) as much output as in 1983 using the 1983 input bundle. However, because over time there was a decline in nutrient stock levels in both systems, the gain in productivity levels was actually lower (1.28 and 0.28, respectively. see Table 1, column 5).

In Table 2, the economic viability of the three systems during 1983, 1984 and 1990 is compared. The traditional bush fallow system is used as the reference base system. In 1983, 1984, and 1990, after accounting for changes in resource abundance and flows, both the alley farming systems (continuous and with fallow) are shown to be relatively more productive than the traditional bush fallow system (Table 2, columns (4), (6), and (8)). The estimated interspatial TFP measures are largely greater than one, indicating that the two alley farming systems produced comparatively more output than the traditional bush fallow system using the latter system's input bundle. Comparison of columns (1)–(3) with columns (4), (6) and (8) indicate that, when resource stock and flows are accounted for, the productivity measures yield different results. The extent of these differences, of course, depends on how significant the changes are in resource stock and flows. In this case, changes in resource stock levels and flows have not been significant enough to alter substantially the productivity measures.

Table 1 *Intertemporal Total Factor Productivity (Sustainability) Indexes for Three Crop–Livestock Systems in Southwestern Nigeria, 1983–84 and 1983–1990*

	Not accounting for resource stock and flows		Accounting for resource stock flows			
	1983–84	1983–1990	1983–1984		1983–90	
			Live-stock	No live-stock	Live-stock	No live-stock
System	(1)	(2)	(3)	(4)	(5)	(6)
Traditional bush fallow (A)	1.24	0.92	1.17*	1.34*	0.78**	0.69**
Continuous alley farming (B)	1.31	1.46	1.08*	1.59*	1.28**	0.64**
Alley farming with fallow (C)	1.17	0.60	1.00*	1.47*	0.60*	0.56*

Note: Numbers with one asterisk indicate the case of a net positive resource flow and those with two asterisks indicate the case of a net negative resource flow.

In order to assess the relative importance of the livestock component in the TFP measures, the analysis was conducted with and without a livestock component. In all cases except for the measurement of the intertemporal TFP during 1983–84, all the productivity measures declined significantly, indicating that livestock do play a significant role in the total productivity of the farm. Therefore when farmers raise animals on the farm (as all of them do) and the productivity measures consider only the crop aspect, results will be biased. A system may said to be non-sustainable when in fact it is as in the case of the continuous alley farming during the period from 1983 to 1990. When the animal component is ignored, the intertemporal TFP measure is only 0.64. When the livestock component is taken into account, the same productivity measure doubles to 1.28 (Table 1, columns (5) and (6)). The same is true for interspatial TFP measures. For example during 1990, when the livestock component is omitted from the analysis, we conclude erroneously that continuous alley farming is economically less viable than the traditional bush fallow system (see Table 2, columns (8) and (9)).

Table 2 *Interspatial Total Factor Productivity (Economic Viability) Indexes for 3 Crop–livestock Systems, in Southwestern Nigeria, during 1983, 1984, 1989 and 1990*

	Not acounting for resource stock and flows			Accounting for resource stock and flows					
	1983	1984	1990	1983		1984		1990	
Systems	(1)	(2)	(3)	Live-stock (4)	No live-stock (5)	Live-stock (7)	No live-stock (8)	Live-stock (9)	No live-stock (10)
Traditional bush fallow (A)	1	1	1	1	1	1	1	1	1
Continuous alley farming (B)	1.9	1.63	1.36	1.87*	1.045*	1.41*	0.94*	1.26*	0.95*
Alley farming with fallow (C)	2.11	2.14	1.45	2.06*	1.045*	1.93*	1.15*	1.18*	1.03*

Note: See Table 1.

CONCLUSIONS

Intertemporal and interspatial total factor productivities adjusted for resource flows and stock provide an excellent framework for evaluating the sustainability and economic viability of production systems. In this paper conventional TFPs are modified to develop a generalized TFP framework in which the contribution of crop and livestock outputs and the unpriced contribution of nutrient stock and flows are taken into account separately and properly. This paper shows that where resource flows and stocks are not negligible, the measures of TFP indexes provide markedly different results from conventional TFP approaches. Disentangling the productivity residual from changes in resource stock and flows honed the productivity residual to finer precision. While the analytical framework presented within this paper is appealing, its successful application depends greatly on data availability. In this paper only changes in major soil nutrients are taken into consideration. The model needs to take into consideration other indications of natural resource degradation, including vegetation and soil physical, chemical and microbiological properties.

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