A General Approach for Evaluating the Economic Viability and Sustainability of Tropical Cropping Systems

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Abstract: This paper presents a methodology for measuring economic viability and agricultural sustainability for new technology evaluation. The approach is based on the concept of interspatial and intertemporal total factor productivity, paying particular attention to the valuation of natural resource stocks and flows. Using a set of data available at the International Institute of Tropical Agriculture, the model is demonstrated by computing the intertemporal and interspatial total factor productivity indices for four cropping systems in southwestern Nigeria. Results show that the sustainability and economic viability measures are sensitive to changes in the stock of nutrients as well as to changes in material input uses and outputs. When common property resource flows are important, the measures provide markedly different results from conventional total factor productivity approaches.

Introduction

Sub-Saharan Africa currently faces serious food problems, manifested in declining per capita food production, growing food imports and accelerating ecological degradation (Ehui and Hertel, 1989; and CGIAR, 1989). New technologies must therefore be developed that not only enhance food production but also maintain ecological stability and preserve the natural resource base; i.e., technologies that are both economically viable and sustainable (BIFAD, 1988). However, there is little guidance in the literature as to what practical methods are to be used for measuring the sustainability and economic viability of tropical cropping systems (CGIAR, 1989; and Lynam and Herdt, 1989). This paper uses recent advances in productivity measurement and economic index numbers to develop a model for measuring economic viability and agricultural sustainability for new technology evaluation.

The next section presents the conceptual framework. First, a generalized model for the measurement of total factor productivity (TFP) is developed. It is followed by the specification of intertemporal and interspatial TFP indices, which are used to measure sustainability and economic viability. In the third section, an empirical example is considered, and, in the fourth section, the paper closes with a summary and some concluding qualifications and comments.

Conceptual Framework

A Generalized Model for Measurement of TFP

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. Agriculture, however, is a sector that uses common-property 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 farmer. 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. When the stock of resources is reduced, the farmer faces an implicit cost in terms of productivity foregone. Conversely, when the stock of resources is increased during the production process (e.g., via nitrogen fixation), 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 biased (Squires and Herrick, 1990). One way to account for this bias is to treat the resource stock as a technological constraint. Accounting for natural resource stocks and flows in sustainability measurement is particularly important since a desirable component of sustainable soil and crop management systems in the tropics is a mechanism that can replenish soil nutrients removed by crops, erosion, and leaching.

Assuming that current prices are known, the maximization problem when changes in common property resources stocks are positive is stated as:

$$(1) \quad Max\ \pi_p = P_{yt}Y_t + P_{zt}Z_t - G(Y_t, Z_t, W_t, B_t, t)$$

where π_t is a measure of aggregate profit in period t, including all benefits and costs of resource exploitation, and 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 and they thus ignore its opportunity cost. Z_t is an externality denoting the net resource flow (i.e., $B_{t+1}-B_t$) in period t. When changes in resource abundance levels are positive, there is a positive externality, and the resulting net resource flow, Z_t, is treated as an output, thus contributing positively to the aggregate profit. Y_t is an index of crop outputs; P_{yt} and P_{zt} are the product and resource flow prices; $G()$ is the variable cost function for the optimal combination of variable of variable inputs, where $\delta G()/\delta B < 0$ and $\delta G()/\delta Z > 0$. 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 (i.e., $B_{t+1}-B_t=-Z_t$). We have thus a negative externality, and Z_t is treated as an input, hence contributing negatively to the aggregate profit. This requires modification of the objective function (1) by replacing the sign before P_tZ_t with a (–) sign and, in this case, $\delta G()/\delta Z < 0$.

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

$$(2) \quad -\frac{\delta Ln\, C}{\delta t} = \frac{P_yY}{C}\dot{Y} + \left(\frac{P_zZ}{C}\dot{Z} - \Sigma_j\frac{W_jX_j}{C}\right)\dot{X}_j - \dot{B}$$

where $C = \Sigma_jW_jX_j = P_yY + P_zZ$ = total revenue, assuming constant returns to scale. Dots above variables imply the logarithm derivative of the associated variable with time.

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

$$(3) \quad -\frac{\delta Ln\, C}{\delta t} = \frac{P_yY}{C}\dot{Y} - \left(\frac{P_zZ}{C}\dot{Z} - \Sigma_j\frac{W_jX_j}{C}\right)\dot{X}_j - \dot{B}$$

where $C = \Sigma_jW_jX_j + P_zZ = P_yY$, assuming constant returns to scale.

Equations (2) and (3) indicate that TFP is measured as the residual after the growth rate of output has been allocated among changes in inputs and resource abundance and flows. It is clear from (2) and (3) that productivity measures are biased unless variations in the resource stocks and flows are accounted for.

Intertemporal and Interspatial TFP Measures

Let us assume that the agricultural production process of cropping system i in period t can be represented by the dual variable cost function:

$$(4) \quad G_{it} = G(Y_{it}, Z_{it}, W_{it}, B_{it}, T_t, D_i)$$

where G_{it} is the cost of production, Y_{it} is crop output, Z_{it} is the change in resource stocks, W_{it} is a vector of input prices, B_{it} is the resource stock, and T_t and D_i denote the intertemporal and interspatial efficiency difference indicators. Derivation of the intertemporal and interspatial TFP indices depends critically on the proper specification of the total cost function

C_{it}, which in turn depends on the nature of Z_{it} (i.e., whether the change in the resource stock is positive or negative). We therefore consider two cases:

Case 1: Net positive change in the resource stock. Assuming constant returns to scale and competitive factor markets, application of Diewert's (1976) quadratic lemma to a logarithmic approximation of (4) gives:

$$\begin{aligned} (5)\quad Ln\, C &= \frac{(R_{yis}+R_{yot})(LnY_{is}-LnY_{ot})}{2} + \frac{(R_{zis}+R_{zot})(LnZ_{is}-LnZ_{ot})}{2} \\ &+ \frac{\Sigma_k(S_{kis}+S_{kot})(LnW_{kis}-LnW_{kot})}{2} - (LnB_{is}-LnB_{ot}) + \theta_{io} + \eta_{st} \end{aligned}$$

where i and o represent two distinct cropping systems and s and t represent two distinct time periods. S_{kis} and S_{kot} are the kth input factor cost shares, R_{yis}, R_{yis}, and R_{yot} are the revenue shares for product Y, and R_{zis} and R_{zot} are (implicit) revenue shares for resource flow Z. θ_{io} and η_{st} denote the interspatial and intertemporal effects and are defined as:

$$(6)\quad \theta_{io} = \frac{\left.\frac{\delta Ln\, G}{\delta D}\right|_{D=D_i} + \left.\frac{\delta Ln\, G}{\delta D}\right|_{D=D_o}}{2}\,(D_i-D_o)$$

$$(7)\quad \eta_{st} = \frac{\left.\frac{\delta Ln\, G}{\delta T}\right|_{T=T_s} + \left.\frac{\delta Ln\, G}{\delta T}\right|_{T=T_t}}{2}\,(T_s-T_t)$$

Equation (5) states that the cost difference across cropping systems and time periods can be broken into six terms: an output effect, a resource flow effect, an input price effect, a resource stock effect, an interspatial effect, and an intertemporal effect.

Following Denny and Fuss (1983), if we want to measure the intertemporal TFP (thus sustainability) of a particular technology, we set $D_i = D_o = 0$. Solving for η_{st} in (5) yields the dual measure of intertemporal productivity for periods s and t:

$$\begin{aligned} (8)\quad \eta_{st} &= (Ln\, G_s-Ln\, G_t) - \frac{(R_{ys}+R_{yt})(Ln\, Y_s-Ln\, Y_t)}{2} - \frac{(R_{zs}+R_{zt})(Ln\, Z_s-Ln\, Z_t)}{2} \\ &- \frac{R_k(S_{ks}+S_{kt})(Ln\, W_{ks}-Ln\, W_{kt})}{2} + (Ln\, B_s-Ln\, B_t) \end{aligned}$$

Similarly, the dual measure of interspatial productivity between system i and reference system o at a particular point in time ($T_s=T_t=0$) is:

$$\begin{aligned} (9)\quad \theta_{io} &= (Ln\, G_i-Ln\, G_o) - \frac{(R_{yi}+R_{yo})(Ln\, Y_i-Ln\, Y_o)}{2} - \frac{(R_{zi}+R_{zo})(Ln\, Z_i-Ln\, Z_o)}{2} \\ &- \frac{R_k(S_{ks}+S_{ko})(Ln\, W_{ki}-Ln\, W_{ko})}{2} + (Ln\, B_i-Ln\, B_o) \end{aligned}$$

If we now turn to the primal space, the Tornqvist approximation to the logarithm change of the cost equation, $G = \Sigma_i W_i X_i$, with respect to time, yields (for periods s and t and systems i and o):

$$\begin{aligned} Ln\,G &= (Ln\,G_{is}-Ln\,G_{ot}) \\ &= \frac{R_k(S_{is}+S_{kot})(Ln\,X_{kis}-Ln\,X_{kot})}{2} + \frac{\Sigma_k(S_{kis}+S_{kot})(Ln\,W_{kis}-Ln\,W_{kot})}{2} \end{aligned} \tag{10}$$

Equating (5) and (10) and solving for $(-\eta_{st})$ and (θ_{io}) gives measures of intertemporal and interspatial productivity in the primal space (Ohta, 1974):

$$\begin{aligned} \tau_{st} = -\eta_{st} &= \frac{(R_{sy}+R_{yt})(Ln\,Y_s-Ln\,Y_t)}{2} + \frac{(R_{zs}+R_{zt})(Ln\,Z_s-Ln\,Z_t)}{2} \\ &- \frac{\Sigma_k(S_{ks}+S_{kt})(Ln\,X_{ks}-Ln\,X_{kt})}{2} - (Ln B_s-Ln B_t) \end{aligned} \tag{11}$$

$$\begin{aligned} \rho_{io} = -\theta_{io} &= \frac{(R_{yi}+R_{yo})(Ln\,Y_i-Ln\,Y_o)}{2} + \frac{(R_{zi}+R_{zo})(Ln\,Z_i-Ln\,Z_o)}{2} \\ &- \frac{\Sigma_k(S_{ki}+S_{ko})(Ln\,X_{ki}-Ln\,X_{ko})}{2} - (Ln\,B_i-Ln\,B_o) \end{aligned} \tag{12}$$

Case 2: Net negative change in the resource stock. Following the same procedure as in case 1, intertemporal and interspatial productivity measures in the primal space are, respectively, given by:

$$\begin{aligned} \tau_{st'} &= (Ln\,Y_s-Ln\,Y_t) - \frac{(S_{zs}+S_{zt})(Ln\,Z_s-Ln\,Z_t)}{2} \\ &- \frac{\Sigma_k(S_{ks}+S_{kt})(Ln\,X_{ks}-Ln\,X_{kt})}{2} - (Ln\,B_s-Ln\,B_t) \end{aligned} \tag{13}$$

$$\begin{aligned} \rho_{io'} &= (Ln\,Y_i-Ln\,Y_o) - \frac{(S_{zi}+S_{zo})(Ln\,Z_i-Ln\,Z_o)}{2} \\ &- \frac{\Sigma_k(S_{ki}+S_{ko})(Ln\,X_{ki}-Ln\,X_{ko})}{2} - (Ln\,B_i-Ln\,B_o) \end{aligned} \tag{14}$$

where S_{zs} and S_{zt} in Equation (13) and S_{zi} and S_{zo} in Equation (14) denote the (implicit) cost shares for depleted resource Z.

An Empirical Example

This section demonstrates how the intertemporal and interspatial total factor productivity measures developed in Equations (11)–(14) can be used to measure the sustainability and economic viability of tropical cropping systems. A set of data is used that was generated during a four-year study by the United Nations University and the International Institute of Tropical Agriculture on the effects of deforestation and land use on soil, hydrology, microclimate, and productivity in the humid coastal belt of Nigeria (Lal and Ghuman, 1989). Four cropping systems, denoted A, B, C, and D, are evaluated for 1986 and 1988, two years for which a complete and balanced data set is available. In System A, land was cleared manually and cropped by a local farmer. Yams, melons, and plantains were grown in 1986, and plantains, melons, and cassava in 1988.

In all other systems, the land was cleared by a tractor equipped with a shear blade, and cropped by the researchers. In System B, cassava, maize, and cowpeas were planted in 1986, and cassava only in 1988. In System C, maize and cassava were planted in 1986, and rice in

1988. All crops in System C were grown in alleys formed by hedgerows of nitrogen-fixing trees or shrubs. In this system, known as alley cropping, the hedgerows were pruned periodically during the cropping season to prevent shading and reduce competition with food crops (Kang *et al*, 1989). In System D, plantains were grown in both years. No fertilizer was used in any of the cropping systems.

Since the cropping systems have multiple crop outputs, an implicit output index is calculated by dividing the total value of all output by a price index obtained by weighting the individual output prices by the revenue share of each crop. A corresponding implicit input quantity index is computed as the ratio of total expenditures on inputs to the weighted material input price. The latter is measured by an index of all material input prices weighted by the cost share of each input. A quantity index for implements used is computed as the ratio of total annual expenditure on capital input and the implicit capital service price. To create an aggregate capital service price, the price of each category of implement is share weighted in the same manner as the aggregate material price index.

To construct the division index for the soil nutrient stock, the total quantities of main soil nutrients—nitrogen, phosphorus, and potassium (in metric tons per hectare)—available in the top soil (0–10 cm) are share weighted. In determining the cost share for the resource stock, the opportunity cost of each soil nutrient was approximated with its replacement cost; i.e., market price of chemical fertilizer. Resource flows are derived as the difference between nutrient abundance levels for a given cropping system between 1986 and 1988 (intertemporal productivity) or between two competing crops.

Intertemporal and interspatial productivity indices for the four cropping systems were calculated and are reported in Tables 1 and 2. In column I, there is no adjustment for changes in resource stocks and flows. Column II provides productivity measures allowing for variations in the resource stock only. In column III, full correction is made by accounting for both changes in resource stocks and flows.

Column III in Table 1 shows that total factor productivity increased for Systems B and C and declined for Systems A and D. Systems B and C produced 6.25 and 11.58 times as much output in 1988 as in 1986 using the 1986 input bundle. Systems B and C can therefore be said to be sustainable over the two-year interval since, after properly accounting for temporal differences in input quality and quantity and resource stocks and flows, they produce more than in the reference year. Systems A and D produced only 0.22 and 0.88 as much output in 1988 as in 1986 using the 1986 input bundle. Thus, A and D can be said to be non-sustainable.[2]

Table 1—Intertemporal Total Factor Productivity (Sustainability) Indices for Four Cropping Systems under Experimental Conditions, in Southwestern Nigeria, 1986–88

System	No Correction I	Resource Stock Only II	Resource Stock and Flow III
A	0.20	0.19*	0.22*
B	6.38	6.14*	6.25*
C	0.02	0.01*	11.58*
D	3.27	4.23**	0.88**

Note: Numbers with one star (*) indicate the case of a net positive change in resource abundance, while those with two stars (**) indicate the case of a net negative change in resource abundance levels.

The economic viability of Systems B, C, and D relative to A is compared in Table 2. In 1986, after accounting for changes in resource abundance and flows, Systems B and C are shown to be relatively less productive than the reference base system. The interspatial TFP indices are estimated to be 0.73 and 0.76 for Systems B and C, respectively, indicating that these systems use relatively more resources and produce a comparatively lower output than

System A. Only System D (in which only plantains were grown) is more productive. In 1988, productivity indices for all the systems show a different pattern. With interspatial TFP indices of 9.26 and 1.12, Systems B and C are now found to be economically more viable than System A. Similarly, with a TFP index of 0.14, System D is found to be economically less viable than the reference base system. The changes in productivity measures in 1988 compared to 1986 are attributable to the changes in soil nutrient status over the two-year period. For example, in System C (where crops are grown in association with leguminous trees), soil nutrients increased by 2.3 percent in 1988 compared to System A, with a revenue share of about 12 percent. In System D, where only plantains are grown, chemical fertility is depleted over time and this is reflected in the lower 1988 productivity measure. Soil nutrients decreased by 21 percent in this system compared to System A, representing about 14 percent of the total cost faced by the farmer in 1988.

Table 2—Interspatial Total Factor Productivity (Economic Viability) Indices for Four Cropping Systems under Experimental Conditions in Southwestern Nigeria, 1986 and 1988

	1986			1988		
System	No Correction I	Resource Stock Only II	Resource Stock and Flow III	No Correction I	Resource Stock Only II	Resource Stock and Flow III
A	1	1	1	1	1	1
B	1.73	2.02**	0.73**	68.50	81.34**	9.26**
C	5.37	6.68**	0.76**	0.37	0.36*	1.12*
D	0.06	0.18*	2.40*	1.04	1.31**	0.14**

Concluding Comments

A model for measuring economic viability and agricultural sustainability for new technology evaluation was presented. The approach was based on the concept of total factor productivity and the growth-accounting procedure modified to accommodate changes in natural resource stocks and flows.

First, using standard optimization techniques, a generalized model of productivity measurement was developed. It was shown that, when common property resource stocks are used, productivity measures using conventional approaches are biased unless changes in resource stocks and flows are fully accounted for. To measure economic viability and sustainability, Denny and Fuss's (1983) interspatial and intertemporal productivity measures were used, which are defined in terms of the productive capacity of a system over space and time. A system is said to be sustainable if, after fully accounting for natural resource stocks and flows, it produces at least the same amount of output as in the reference year. Similarly, System A is said to be economically more viable then System B if, after completely accounting for natural resource stocks and flows and conventional inputs, A produces relatively more output than B.

A set of data available at the International Institute of Tropical Agriculture were used to compute the intertemporal and interspatial total factor productivity indices for four cropping systems in southwestern Nigeria. Results show that the sustainability and economic viability measures are sensitive to changes in the stock of soil nutrients as well as to changes in material input uses and outputs. Where common property resource flows are important, the measures provide markedly different results from conventional TFP approaches. The alley cropping system in which crops are grown between rows of leguminous fixing trees is shown to be sustainable and economically more viable than other systems after completely accounting for (positive) changes in natural resource stocks and flows.

Notes

[1] International Livestock Centre for Africa and International Institute of Tropical Agriculture, respectively.

[2] Note from Table 1 that completely accounting for changes in resource levels and flows substantially alters the productivity measures. This is particularly true for System C in which the hedgerow trees fix atmospheric nitrogen and recycle nutrients, and System D, where the plantains heavily deplete the soil of its nutrients. Note that in System C, if the nitrogen contribution of the trees is not accounted for, the intertemporal productivity index is lower than unity (column I), leading to the erroneous conclusion that the system is not sustainable.

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Discussion Opening—*Miguel A. López-Pereira* (Centro Internacional de Mejoramiento de Maiz y Trigo)

The economics of sustainability of farming systems in developing countries has become a popular research topic as the concept becomes relevant to more countries where natural resources are dwindling due to, *inter alia*, natural causes, population growth, and inefficient farming methods, especially by small farmers on low fertility land (hillsides, forests).

In this paper, a formal treatment of the economics of sustainability is attempted. In other studies on sustainability, a more empirical approach to measuring the long-term feasibility of farming systems has been followed. The authors attempt to develop a model in which flows of nutrients and other factors determining the long-term viability of farming systems are accounted for when assessing their economic feasibility. However, the complicated set of equations seems to indicate that the model has some basic shortcomings that should be addressed.

With regard to the intertemporal component, the model does not appear to account for time when measuring the costs and benefits of inputs and products (discount rate). If the time dimension is to be included in the analysis, there has to be a discount rate to make estimations over time consistent.

The empirical example used to demonstrate the application of the conceptual model is also inadequate. Is two years of farming enough to provide a measure of the sustainability (i.e., long-term viability) of a given farming system? There are many factors in different farming systems that need much more time to have any effect on sustainability, such as the residual effect of nutrients added to the soil and the effects of certain rotations on soil fertility and disease and pest resistance. Many of these factors have an effect on the sustainability of the system that is not linear over time, so that long-run projections based on only a few seasons are not useful. A full cropping cycle including a fallow period, usually requiring seven to ten years, would be the minimum required to measure sustainability. If the resource and product flows have not decreased over the cycle, then the system could be considered sustainable.

How is the model applied in practice; i.e., how are the *Z*s measured and translated to monetary values or to what the authors call "implicit revenue shares"? Soil nutrient flows such as nitrogen fertilizer (as used by authors in the example) are probably easy to measure. But one may run into measurement problems when including changes in other important factors such as soil structure, or the effect of a farming system on the genetic diversity of species in a forest (if we were analysing a system that requires the clearing of forests). Valuing these more intangible factors may be very difficult. Even given limitations regarding length, it would have been useful for researchers interested in applying the model elsewhere if the paper had a section or an appendix showing how one moves from the model equations to the figures shown in the tables of their example.

How is interspatial productivity compared among more than two cropping systems? Are these comparisons transitive; i.e., if $A > B$ and $B > C$, is then $A > C$? Also, can it be concluded that System C is more sustainable and economically viable than System B? Note that interspatial TFP is greater in B than in C in Table 2, and from the intertemporal TFP of Table 1, System C is better than System B.

The model, which is an aggregate model, may be useful for selecting the best of a group of systems and may provide useful information to policy makers. However, many of the policy measures necessary to implement the socially optimal system at the farm level may pose real challenges. Individual farmers may act differently from what is considered a social optimum. Cases of rented land, for example, come to mind. If there are no long- term rental agreements, which is the rule in developing countries, farmers will not care for positive nutrient flows if they will not be able to use them. On the contrary, they will try to extract as much as possible from the soil in the form of crop products, with as few inputs as possible.

[Other discussion of this paper and the authors' reply appear on the following page.]

General Discussion—*Xiao Hui, Rapporteur* (Beijing Agricultural University)

On the Musgrave paper, the danger of transferring site-specific production functions from developed countries to developing countries was raised. Even though the generation of site-specific production functions is very expensive, this should be an ideal objective. Agricultural economists can and should use existing agronomic data for economic specification of production response. It was also suggested that the use of crop models of the type developed by the authors has not led to significant successes. The authors were asked if they see scope for future breakthroughs based on the use of such a model.

In reply, Musgrave indicated that while they are aware that site specificity is very important, constructing so many site-specific production functions is very time consuming. Farmers have been told how to irrigate; this cannot wait for the generation of site-specific production functions. Therefore, transferring models from developed countries is the only way. While the production function is less site specific for decision making, the transferred production function has proved very useful for decision making in Australia.

On the Featherstone, Osunsan, and Biere paper, since the research work has potential for better decision making, the authors were asked where the pay-offs lie, and what the implications are for decision making at the farm or policy level. The crop simulation models are very useful. The authors were asked if the model can be applied to developing countries, and whether the crop growth component can be applied to the mixed cropping systems common in LDCs. In Africa, for example, crops have many disease and insect problems, so that to make results more realistic, the authors need to consider disease and insects, which are endogenous variables in production. Since evapotranspiration is a more meaningful parameter than soil moisture in the model, the authors were asked why they use soil moisture rather than evapotranspiration.

Featherstone replied that the models can be applied in developing countries by using different input variables. The generation of the probability function is based on 29 years of daily data. The problem of diseases and insect pests can be solved by introducing more constraints to the models. Water moisture is a more basic input than evapotranspiration and is therefore estimated in the model.

Ehui was asked about the implications for research priorities and for designing research strategies. The authors were strongly advised to spend less time on issues of definition and much more on clarifying the rather complicated methodology and interpretation of the results.

In reply, Ehui emphasized that the model was derived for actual uses, based on a short comparison year by year. Two years' data are not enough to show the results; the minimum time is three years. Moreover, the model is very practical and can be used very easily.

Participants in the discussion included R. Dumsday (La Trobe University), D.A.G. Green (University College of Wales), W. Grisley (Centro Internacional de Agricultura Tropical), and H. Jansen (AVRDC).