ELSEVIER

Agricultural Economics 14 (1996) 45-60

AGRICULTURAL
ECONOMICS

Quantifying the socio-economic determinants of sustainable crop production: an application to wheat cultivation in the Tarai of Nepal

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Accepted 27 August 1995

Abstract

This study specifies a procedure to quantify the determinants of sustainable crop production, and applies the method to wheat cultivation in the Tarai of Nepal. Three aspects of sustainability were considered. First, the fertility of the land was found to have deteriorated owing to long-term practices incompatible with soil and drainage conditions. Three-quarters of the farmers had reduced land fertility and for one-third of them the wheat yield was at least 20% lower than for farmers who applied farmyard manure to every crop and adopted a rotation consistent with soil and drainage conditions. Secondly, the study found that it was possible to improve resource-use efficiency in wheat production to give 25% higher production at current levels, type, and quality of farm resources. Resource-use efficiency was significantly related to farm management practices such as crop stand, variety, disease, and land preparation quality, and socio-economic factors such as off-farm job opportunities, poor plot accessibility, and migration. Thirdly, the increasing population pressure on land, decreasing livestock number per cropped area, and diminishing fuel wood sources, significantly reduced farm-based nutrient cycling because farmyard manure had to be used for fuel. This had implications for the higher use of the fossil-based inputs in crop production.

1. Introduction

The notion of sustainability has been defined and characterized in vastly different ways — from the resilience of individual agroecosystems to food security in the face of global climate change (Harrington, 1990). The Technical Advisory Committee of the Consultative Group on International Agriculture Research defined sustainability as ''the successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources'' (Plucknett, 1990). Alternative approaches for measuring sustainability have been suggested and used according to what is to be sustained.[1] Rather than becoming involved in the question of how to measure sustainability, this paper takes up a more practical issue of what determines sustainable crop production.

I intend to quantify the socio-economic determi-

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[1] Lynam and Herdt (1989) suggested total factor productivity (TFP) be estimated to measure the sustainability of a production system; Harrington (1990) reviewed alternative approaches, including yield trends, TFP, and the production function to measure sustainability; Ehui and Spencer (1993) estimated the interspatial and intertemporal TFP of alternative farming systems, paying special attention to valuation of natural stock and flows. Cassman and Pingali (1993) estimated TFP for long-term experimental and field monitoring data and concluded that resources under intensive rice production are deteriorating. Ali and Velasco (1993) showed the deterioration in resource productivity under all intensive cropping systems using yield trends, return per unit of inputs, TFP, and the production function analysis.

0169-5150/96/$15.00
SSDI 0169-5150(95)01161-7

nants of sustainability in terms of control variables (tillage practices, crop rotation, erosion control methods, etc.) without investigating how the control variables affect the state variables (soil nutrient, soil aeration, organic matter, etc.). Alternatively, one can monitor a field or plant for a long time to see how state variables change, with or without looking at what control variables cause those changes. While the latter approach is important for theoretical knowledge, the former approach can highlight the immediate problems and suggest possible solutions for a sustainable production system.

Because sustainability is a multidimensional concept (Harwood, 1987), different factors may contribute to the sustainability of each dimension. However, three aspects of sustainability are considered in this paper: resource quality, resource-use efficiency and changes in internal nutrient cycling.

1.1. Resource quality

Resource quality under crop production is affected by farm management practices continuously practised over an extended period. In this analysis, these practices will be called long-term practices, and the extent to which resource quality is affected by these practices will be measured through long-term sustainability indices. Some of these practices may have a positive effect on resource quality, such as for example continuous use of farmyard manure or green manure, while others may impair it such as use of the same rotation year after year, use of chemicals, etc. The farm-specific long-term sustainability indices (LTSI) will be estimated by considering the marginal effect of all these practices on production.

1.2. Resource-use efficiency

Efficient use of variable inputs is an important part of sustainability (Harwood, 1987), which implies either fewer inputs to produce the same level of output or higher output at the same level of inputs. This improves the productivity of fixed resources, and thus sustainability of the production system. An index of resource-use inefficiency (RUII), after controlling the effect of long-term management practices, will be estimated for each farmer, and its determinants in terms of agronomic and socio-economic factors will be quantified. The RUII will be totaled in the LTSI to estimate the sustainable resource-use efficiency index (SRUEI).

1.3. Changes in internal nutrient cycling

The agroecological view of sustainability emphasizes nutrient and energy cycling, and thereby reduction in the use of external inputs (Francis, 1976; Altieri, 1987). Consequently, monitoring the causes of change in nutrient cycling is perceived as fundamental to understanding the determinants of a sustainable production system. In this analysis, the determinants of farmyard manure supply will be quantified.

2. Theoretical framework

This section elucidates a theoretical framework for constructing the LTSI, RUII, and SRUEI. A model is delineated to quantify the determinants of farmyard manure supply to crop production.

2.1. Long-term sustainability indices

Assume farmers have the option of adopting different types of a given long-term management practice, say A, B, or C on their piece of land. These types may be different crop rotations, fertility management methods, irrigation sources, or number of years for which a given rotation or input was used on a parcel. Without going into the details of how a given type of management practice is selected by farmers considering its short- and long-term impacts, the purpose here is to quantify its effect on land productivity ostensibly through altering land quality. One way is to observe the effect year after year, but it may take so long that by the time some conclusions are derived, the interest in sustainability may have faded. I propose to measure the effect of long-term practices on sustainability in retrospect by comparing the productivity of different parcels on which alternative options of management practices were adopted in the past. For this, the long-term effect of the management options needs to be isolated from the short-term effect created by varying physical inputs levels and land types. This can be done by including the management options in the production function as variables, along with the levels of physical inputs and resource types. The following production function (in vector notation) can be specified for this purpose

$$Y = f(X, D, Q)\, e^{v} \tag{1}$$

where Y is the output, X is a vector of variable inputs, D denotes soil or land type variables, Q is a vector of long-term practices assumed to have carry-over impact on land quality, and v connotes random error due to mis-specification of the model, measurement error, missing variables and other random shocks, and e is the exponential term.

The coefficients of long-term farm management practices adopted in the past can be used to measure their accumulated carry-over effect on production. The farm-specific long-term sustainability indices can be estimated by taking the total derivative of Eq. (1) with respect to all long-term practices and evaluating it at the farm level of input use and type of resources.

2.2. Resource-use efficiency indices

To estimate the resource-use efficiency index, the production function in Eq. (1) is modified as below

$$Y = f(X, D, Q)\, e^{(v-u)} \tag{2}$$

The error term now has two parts; e^{v} is as defined in Eq. (1), while e^{-u} is a ratio of actual yield to the maximum possible yield, at the level of farm-specific variable inputs and soil type. If the value of e^{-u} is 1, the farmer is on the frontier of the production function and is resource efficient. His practices and socio-economic environment maximize output from the resources he employs, or minimize the resource-use for the level of output he achieves. If the value of e^{-u} is below 1, the farmer is below the frontier production function. His practices and socio-economic environments produce less than the maximum possible output (MPO), or he has to use more inputs than currently he is applying to achieve the MPO. The value of e^{-u}, therefore, represents the resource-use efficiency, and $1 - e^{-u}$ will give RUII.

Eq. (2) can be estimated using the Maximum Likelihood Estimation (MLE) technique if the nature of the density function for u and v is specified (Aigner et al., 1977). The frontier in Eq. (2) can also be estimated by the deterministic rather than the stochastic approach. Both stochastic and deterministic approaches have further variations depending upon the assumptions made about the distribution of the efficiency term. Moreover, there are other approaches to estimate resource-use efficiency. Ali and Byerlee (1991), Battese (1992), and Bravo-Ureta and Pinheiro (1993) have reviewed these approaches extensively to measure farm-specific and average resource-use efficiency. Bravo-Ureta and Rieger (1990) found that the efficiency values obtained by different methods were highly correlated, gave similar ordinal rankings of the farms, but that the efficiency levels estimated through the deterministic approach are generally lower than those obtained using the stochastic approach. This may be because the efficiency estimates obtained using the former approach include a random error component.

In this analysis, MLE technique is used to estimate the production frontier by assuming v to be normally distributed and u to have a truncated (half) normal distribution. To isolate e^{v} from e^{-u}, the expected value of u is estimated using the formulation suggested by Jondrow et al. (1982).

$$E(u/v) = \sigma^{*}\left[\left(\frac{f(.)}{1-F(.)}\right) - \left(\frac{R\lambda}{\sigma}\right)\right] \tag{3}$$

where σ is standard deviation of the total error term $R = u + v$, $\sigma^{*} = \sigma_u . \sigma_v / \sigma$, $\lambda = \sigma_u / \sigma_v$, $\sigma = / \sigma u^2 + \sigma v^2$, and $f(.)$ and $F(.)$ represent the standard normal density and distribution function, respectively, evaluated at $R\lambda/\sigma$. R is obtained by substituting the farm level of input use and resource type in the estimated function of Eq. (2), σ_u^2 and σ_v^2 are standard errors of u and v, respectively, and are the outcome of the MLE estimation. The resource-use efficiency index is then measured by taking the natural logarithm of $-u$.

2.3. Nutrient cycling

To see what determines domestically produced soil nutrient supply from farmyard manure, the following equation is used

$$FYM = g(S, PI, FS, FU, D)\, e^{l} \tag{4}$$

where FYM is farmyard manure applied to a crop, S

is the number of animals, *PI* is population density, *FS* is farm area, *FU* is fuel source, *l* is random error, and *e* and *D* are as defined in Eq. (1).

The future availability of farmyard manure will be predicted on the basis of past trends in population, cropped area, and livestock population. The substitution of fertilizer for farmyard manure will be estimated based on the expected future availability of the latter, and marginal rate of technical substitution between the two inputs.

3. The study area, sampling, and data collection

The above framework to quantify the determinants of the three aspects of sustainability was applied to wheat cultivation in the Tarai of Nepal which accounted for about 15% of the total cropped area, and grown in the rice–wheat system.

Wheat accounts for a minor proportion of the total grain production as well as of the rice–wheat system in Nepal (rice dominates the system). Although the framework developed above can be used for any crop, wheat was selected because it was perceived to have more sustainability problems than rice. This is because wheat production has spread in what is presumably an environment optimal for rice production, but marginal for wheat cultivation (the heavy clay and medium soils that dominate the area are better for rice cultivation, but marginal for wheat). Moreover, the stagnation in wheat productivity and impressive growth rate in rice yield during the 1980s was an indication that a sustainability problem was more associated with the former crop (wheat yield changed at 0.94% and −0.12%, while rice yield increased at 0.89% and 1.89% per annum during the 1970s and 1980s, respectively).

The Rupandehi district, an intensive wheat growing area in the Tarai of Nepal, was selected for monitoring input use, management practices, and resource quality in wheat. Average total annual rainfall in the district is around 1600 mm. Light precipitation may be expected in December–March, and mean temperature is lowest (15°C) in January, ideal for wheat production.

A random sample of 170 farmers was selected from the district. The farmers were pre-stratified according to whether they were beneficiaries of the Bhairahawa Lumbini Groundwater project, a tubewell irrigation development project funded by the World Bank. The sample included 82 farmers from the groundwater project and an additional 88 farmers from outside the project, randomly selected from each strata.

A major wheat growing parcel from each farm was picked for detailed observations on input quantities and farm management practices, especially the long-term management practices followed in retrospect. Two such practices identified for this analysis were crop rotation and continuity in farmyard manure application. Survey enumeration was conducted during 1991 by scientists from the Bhairahawa Wheat Research Farm, CIMMYT, and IRRI, and extension workers from the district Agricultural Development Office (ADO). For more details on data collection, see Giri et al. (1993).

4. The empirical models

A translog production function, suggested by Christensen et al. (1973), was estimated in this study. The function was specified as follows:

$$\begin{aligned}\ln Y_j = {} & \ln a_0 + \sum_{i=1}^{4} a_i \ln X_{ij} \\ & + 1/2 \sum_{i=1}^{4} \sum_{g=1}^{4} b_{ig}(\ln X_{ij} \times \ln X_{ij}) \\ & + \sum_{k=1}^{2} c_k D_{kj} + \sum_{t=1}^{2} d_t Q_{tj} \\ & + 1/2 \sum_{i=1}^{4} \sum_{k=1}^{2} f_{ik}(\ln X_{ij} \times D_{kj}) \\ & + 1/2 \sum_{i=1}^{4} h_{i1}(\ln X_{ij} \times Q_{1j}) \\ & + 1/2 \sum_{k=1}^{2} \sum_{0 \neq k}^{2} r_{ko}(D_{kj} \times D_{oj}) \\ & + 1/2 \sum_{k=1}^{2} s_{k1}(D_{kj} \times Q_{1j}) + u_j + v_j \qquad (5)\end{aligned}$$

Table 1
Definition and measurement methods of the variables used in Eq. (5)

Variable group	Variable name	Measurement method
Output (Y)	Output (Y)	Wheat output (kg)
Variable inputs	(i) Fertilizer (X_1)	Kilogram of fertilizer nutrients including nitrogen, phosphorus and potash
	(ii) Irrigation (X_2)	Number of irrigations [a]
	(iii) Farmyard manure (X_3)	As farmyard manure was assumed to be a function of household characteristics, the estimated values (t) from Eq. (8) were used
	(iv) Weeding (X_4)	As a dummy variable having a value of 1 if the parcel is weeded, 0 otherwise
Soil and land type (D)	(i) Soil type (D_1)	A dummy variable having a value of 1 when soil is heavy and cloddy, 0 otherwise
	(ii) Waterlogging (D_2)	A dummy variable having a value of 1 if parcel is not waterlogged, 0 if waterlogged
Long-term practices (Q) [b]	(i) Rotation (Q_1)	A dummy variable assigned a value of 1 when the rice–wheat rotation was followed on a parcel continuously for the past 3 years, 0 when the rotation was interrupted with another crop in these years
	(ii) Continuity in farmyard manure application (Q_2)	A dummy variable having a value of 1 when farmyard manure was not applied to every crop and 0 when it was applied to every crop during the past 3 years

[a] The number of irrigations may be a sceptical variable if it is not uniform on different farms or different points of time. However, water was purchased from a publicly owned tubewell, and time standard for each irrigation was quite uniform.

[b] Owing to the limitation of the available data, only two long-term management practices defined in binary form were included in the analysis. These can be roughly defined as a continuous variable, such as number of years rice–wheat rotation continued on a parcel. Many more long-term practices, such as number of years a field was irrigated, fertilized, etc. can be included in the analysis.

where $j = 1, 2...n$ for wheat parcels, g, $i = 1...4$ are inputs, and Y, X, D, Q, u_j, and v_j are defined in Eqs. (1) and (2). The definitions of the specific variables in each set are given in Table 1. a_0, a_i, b_{ig}, c_k, d_t, f_{ik}, h_{i1}, r_{ko}, and s_{k1} are the parameters to be estimated for intercept, physical inputs, interaction across the ith and gth physical inputs, dummy variables on soil and land type (i.e. resource quality), dummy variables on long-term practices, interaction between the ith physical inputs and the dummy variable on resource quality, interaction between the ith physical input and 1st dummy variable on long-term practices, interaction across kth and oth dummy variables on resource quality, and interaction between kth dummy variables on resource quality and 1st dummy variables on long-term practices, respectively. All except dummy variables are expressed in natural logarithmic form on a per hectare basis.

To keep the model manageable, only limited and theoretically plausible interactions between physical inputs and dummy variables were included in the model. For example, fertilizer nutrient and farmyard manure were assumed to interact with soil conditions and cropping pattern history, but not with drainage conditions. Similarly, interaction between the dummy variable for farmyard manure frequency and other variables was excluded.

The production elasticities of the variable inputs (fertilizer, farm manure, and irrigation) were estimated by taking the first partial derivative of Eq. (5) with respect to each input, and evaluating them at the farm-specific input use. The marginal productivities were estimated as farm-specific elasticities multiplied by farm-specific average output, approximated as (Y_j/X_j).

The elasticities of long-term management practices were estimated by taking the first partial derivative of Eq. (5) with respect to individual practice, and evaluating it at the farm-specific levels of input use and soil type. Similarly, long-term farm-specific sustainability index was estimated by taking the first total derivative of Eq. (5) with respect to all long-term practices and evaluating it again at the farm-specific level of input use and soil type, i.e.

$$\text{LTSI} = \sum_{t=1}^{2} d_t + 1/2 \sum_{i=1}^{4} h_{1i}(\ln X_i) + 1/2 \sum_{k=1}^{2} s_{k1}(D_k) \qquad (6)$$

where LTSI is the long-term sustainability index. The LTSI shows the total percentage change in the productivity of a parcel (which is an accumulated effect) brought about by following particular types of long-term practices for many years compared with a parcel where another type (base-run) of practices were adopted. In this analysis the base-run practices were assumed to be the continuous application of farmyard manure and non-continuous rice–wheat rotation, which forced the value of d_t, h_{1i} and s_{k1} equal to zero. The value of LTSI would be 0 when base-run practices assumed to give no change in land quality were used; positive when resource quality had improved; negative when it deteriorated; depending upon the sign and relative magnitude of d_t, h_{1i} and s_{k1} and quantities of X_i.

The RUII was estimated using Eq. (3), after controlling for the sustainability effect of long-run management practices. As RUII shows percentage loss in output due to inefficient use of resources, it can be converted into negative values to make it consistent with LTSI. The RUII and LTSI can thus be summed to estimate SRUEI. When SRUEI is positive this indicates a net improvement in productivity due to the short- and long-term effects of all management practices, and vice versa when it is negative. The

Table 2
Socio-economic and agronomic characteristics in Rupandehi, Nepal, 1990–1991

Characteristics	Group	Frequency	Percent
Socio-economic characteristics			
Family size	1–4	23	13
	5–8	86	50
	9–12	50	31
	≥ 13	11	6
Family members involved in off-farm activities	0	123	72
	1–2	36	21
	> 2	11	7
Migrant	Migrant	57	34
	Indigenous	113	66
Tenure	Owned	161	95
	Rented, tenant	9	5
Fertilizer	Non-users	9	5
	Users	161	95
Irrigation	Rainfed	69	41
	Irrigated	101	59
Agronomic characteristics			
Soil type	Light	26	15
	Medium	91	54
	Heavy	53	31
Drainage	Good	145	85
	Poor	25	15
No. of times weeded	None	117	67
	Once	6	3
	Twice	0	0
	Gathered for feed	47	30
Land type	Khala	29	17
	Osahniya	100	59
	Danda	41	24
Crop history	Cont. rice–wheat	126	74
	Non-cont. rice–wheat	44	26
Continuity in farmyard manure application	Cont.	85	50
	Non-cont.	85	50

Table 3
Mean values of wheat inputs and yield in Rupandehi, Nepal, 1990–1991

Input/output	Minimum	Maximum	Mean	SD
Farm size (ha)	0.3	12.6	2.0	1.9
No. of plowings	1.0	10.0	4.0	1.1
Fertilizer nutrient (kg ha^{-1})	0	258.0	85.0	47.1
N	0	198.0	56.0	54.7
P	0	82.0	28.0	18.1
K	0	60.0	1.0	6.6
Farmyard manure (t ha^{-1})	0	20.0	4.0	4.6
No. of irrigations	0	5.0	1.0	1.1
Yield (t ha^{-1})	0.02	4.3	1.7	0.71
Sample size	170			

determinants of the resource-use efficiency index were quantified by the following equation

$$\begin{aligned} e^{-u_j} = {} & p_0 + p_1(\mathrm{LPQ}) + p_2(\mathrm{CSVAR}) + p_3(\mathrm{SEEDT}) \\ & + p_4(\mathrm{DIS}) + p_5(\mathrm{RATS}) + p_6(\mathrm{PLTP}) \\ & + p_7(\mathrm{VAR}) + p_8(\mathrm{MIG}) + p_9(\mathrm{MACH}) \\ & + p_{10}(\mathrm{IRRD}) + p_{11}(\mathrm{TENUR}) \\ & + p_{12}(\mathrm{PLOTA}) + p_{13}(\mathrm{FAMS}) + p_{14}(\mathrm{NPAR}) \\ & + p_{15}(FA) + p_{16}(\mathrm{OFFARM}) + w_j \end{aligned} \tag{7}$$

Two groups of variables were included in the equation: (1) farm management practices, which include land preparation quality (LPQ), crop stand variability (CSVAR), time of seeding (SEEDT), and dummies for disease (DIS), rats (RATS), plant population (PLTP) and variety (VAR); (2) socio-economic environments, which include dummies for migration (MIG), machine (MACH), irrigation (IRRD), tenure (TENUR), plot accessibility (PLOTA), family size (FAMS), farm area (FA), number of parcels (NPAR), and off-farm jobs (OFFARM), and w_j is an error term assumed to be randomly and normally distributed.

The farmyard manure applied per hectare to the wheat crop (FYM) was hypothesized to depend upon the factors captured in the following equation

$$\begin{aligned} \mathrm{FYM} = {} & A_0 + A_1(S) + A_2(PI) + A_3(FS) \\ & + A_4(FU) + A_5(D) \end{aligned} \tag{8}$$

where number of animals (S) was estimated in Standard Animal Units (SAU) [2] per hectare, population intensity (PI) as number of adult equivalent family members per SAU, farm area (FS) in hectares, source of fuel energy (FU) as a dummy variable having the value of 1 if farmyard manure is the only source of fuel energy and 0 if it is supplemented with firewood, and land type (D) as a dummy variable having the value of 1 for upland and 0 otherwise.

5. Results and discussion

5.1. Basic characteristics of the sample farmers

The characteristics of the sample farmers are reported in Tables 2 and 3. Most farmers' families had five to eight members. More than one quarter of farmers' family were engaged in off-farm activities, and about one third had migrated from the hills. Forty percent of the farmers did not have any access to irrigation while most farmers used fertilizer.

About 31% of the parcels had heavy soils, and 15% were waterlogged. Thirty percent of farmers weeded their fields largely to gather fodder for livestock. Three major land types may be distinguished.

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[2] SAU are calculated using the following conversion ratios (RONCO Consulting Corp. and AGRI-BI-CON International, 1991, Annex IV, p. 29)

$$\begin{aligned} \mathrm{SAU} = {} & (\text{male cattle} \times 1.3) + (\text{female cattle} \times 1) \\ & + (\text{young cattle} \times 0.5) + (\text{sheep and goat} \times 0.19) \\ & + (\text{male buffalo} \times 1.5) + (\text{female buffalo} \times 1.25) \\ & + (\text{young buffalo} \times 0.5) \end{aligned}$$

Table 4
OLS and MLE estimates of translog production function for wheat, Rupandehi, Nepal

Variable	OLS		MLE	
	Coefficient	SE	Coefficient	SE
Physical inputs				
Fertilizer (kg ha^{-1})	−0.0096	0.0403	−0.0042	0.1402
Irrigation (no. of irrigations)	0.0525	0.0754	0.0028	0.0950
Farmyard manure (t ha^{-1})	0.0796 **	0.0383	0.0738	0.0792
Weeding (1 if weeding done, 0 if not done)	0.7264 ***	0.2057	0.7445 ***	0.2384
Squared terms				
Fertilizer × Fertilizer	−0.0373 ***	0.0095	0.0341 ***	0.0122
Irrigation × Irrigation	0.0048	0.0210	−0.0118	0.0251
Farmyard manure × Farmyard manure	0.0157	0.0100	0.0139	0.0116
Interactions among inputs				
Irrigation × Fertilizer	−0.0150 **	0.0081	−0.0142	0.0139
Farmyard manure × Fertilizer	0.0147 *	0.0104	0.0125	0.0324
Farmyard manure × Irrigation	0.0104 **	0.0049	0.0095 **	0.0053
Weeding × Fertilizer	−0.1758 **	0.0758	−0.1703 **	0.0940
Weeding × Irrigation	0.0046	0.0372	−0.0057	0.0349
Weeding × Farmyard manure	−0.0920 **	0.0409	−0.0839 **	0.0390
Resource quality				
Soil type (1 = heavy, 0 = otherwise)	−0.2502	0.2556	−0.2760	0.3352
Drainage (1 = good, 0 = otherwise)	0.0570	0.1285	0.1233	0.1678
Dummy on long-term practices				
Crop history (1 = cont. rice–wheat, 0 = non-cont. rice–wheat)	−0.4929 **	0.2395	−0.4835	0.7168
Farmyard manure frequency (1 = not for every crop, 0 = for every crop)	−0.1849 **	0.0835	−0.1692 **	0.0792
Interaction of dummy and physical inputs				
Soil type × Fertilizer	0.2271 **	0.0927	0.2221 **	0.1320
Soil type × Irrigation	0.0348	0.0360	0.0326	0.0387
Soil type × Farmyard manure	0.0041	0.0335	0.0073	0.0373
Drainage × Irrigation	0.0810 **	0.0558	0.0877 *	0.0730
Interaction of dummy on long-term practices and physical inputs				
Crop history × Fertilizer	0.1645 **	0.0751	0.1585	0.2956
Crop history × Irrigation	−0.0316	0.0443	−0.0571 *	0.0541
Crop history × Farmyard manure	−0.1078 ***	0.0367	−0.1074 **	0.0466
Interaction among dummies				
Soil type × Crop history	−0.4608 *	0.2830	−0.4384	0.3659
Soil type × Weeding	−0.4888 **	0.2858	−0.4017 *	0.2586
Soil type × Drainage	0.6434 **	0.3630	0.6160	0.4964
Crop history × Drainage	−0.5029 *	0.2939	−0.5791 **	0.3021
Intercept	7.0573 ***	0.2577	7.3484 ***	0.6241
R^2	–	0.5076	–	–
Log-likelihood function	–	–	−29.48	–
Lambda (G)	–	–	2.1628 **	0.9834
Sigma (S)	–	–	0.4292	0.0547

Asterisks indicate significance: *** 1%; ** 10%; * 15%.

Lower terraces (locally khala) are characterized by heavier soils and poor drainage. Middle terraces (osahaniya) are characterized by lighter soils and few drainage problems while upper terraces (danda) are well-drained.

The most important variables for the purpose of this analysis concerned the history of the parcels with respect to long-term farm management practices. Two such practices were crop rotation and continuity in farmyard manure application. Different types of rotation followed in the area were continuous rice–wheat, rice–fallow, or rice–wheat–mustard On about 26% of the sample parcels, the rice–wheat rotation during the second year was interrupted by other rotations, and about 50% of parcels did not receive continuous farmyard manure for the last 3 years (Table 2).

Mean farm size was 2 ha, with a range of 0.3–12.6 ha. The mean rate of NPK fertilizer applied to the wheat crop was 85 kg ha^{-1}. The average amount of farmyard manure was 4 t ha^{-1}, and average number of irrigations was one. The wheat yield varied from 20 kg ha^{-1} to 4.3 t ha^{-1}, with an average of 1.7 t ha^{-1} (Table 3).

5.2. Estimates of production function, elasticities, and marginal productivities

The average production function, assuming only v_j present as in Eq. (1), was estimated using the Ordinary Least Square (OLS) method. The frontier function was estimated using the MLE approach through the LIMDEP program. The results of the OLS and MLE estimations are given in Table 4.

The hypothesis of separability was tested by testing whether the coefficients of the interaction terms equaled zero. A high F-value rejected the hypothesis in favor of positive contributions of the interaction terms in explaining the variability in wheat yield. This implies that the translog function gave a better fit than the Cobb–Douglas function.

In a translog function, production elasticities and marginal productivities vary with the input level. A production function is said to be well behaved if it is monotonically increasing and concave in input quantities (Kumbhakar, 1994). The monotonocity assumption implies positive marginal productivities of different inputs within the data range (Carbo and Meller, 1979), while concavity was tested by checking the matrix specified in Kumbhakar (1994) as negative semi-definite. For non-zero input-users, both production elasticities and marginal productivities were positive on all the data points, and the specified matrix fulfilled the concavity condition.

The average sample elasticities and marginal productivities of farmyard manure, fertilizer, and irrigation were estimated from the OLS function under alternative environments, and the results are reported in Table 5. Similarly, the elasticities of qualitative variables (weeding, crop history, soil type, drainage conditions) are reported in Table 6. The results are reported only for those groups having more than ten observations.

Marginal productivities varied according to crop-rotation history, soils, drainage, and weeding (Table 6). An additional 1 t of farmyard manure increased production by 42.1 kg ha^{-1} on a parcel which was not weeded, had light soils, good drainage, and non-continuous rice–wheat rotation (environment 1). The increase was only 4.6 kg ha^{-1} where the field was weeded, with heavy soil, good drainage and continuous rice–wheat rotation (environment 5). The addition of 1 kg ha^{-1} of fertilizer increased production by 2.7 kg ha^{-1} and 1.5 kg ha^{-1} if the environments were classified as 3 and 5, respectively. An additional irrigation increased production by 35.2 kg ha^{-1} and 30.6 kg ha^{-1} under the environments classified as 1 and 2, respectively.

The optimum and actual fertilizer quantities are compared in Table 5. Wide variation in the optimum levels of fertilizer use was observed under alternative environments, indicating a need to develop input use recommendation according to farmers' environments (Ali, 1995). For example, the optimum fertilizer use varied from 167 kg ha^{-1} when the field was not weeded, soil was heavy but well drained, having been under continuous rice–wheat rotation (environment 3) to only 67 kg ha^{-1} when the field was not weeded, soil was medium or light and well drained, having been under non-continuous rice–wheat rotation (environment 1). Similar variations for the optimum levels of farmyard manure, and irrigation were observed under alternative environments (results not reported in the table).

Generally, farmers were not reaching the optimum levels with respect to their farm-specific envi-

Table 5
Production elasticities and marginal productivities of the physical inputs under different environments in wheat production, Rupandehi, Nepal

Environment	Environment				Frequency	Elasticities			Marginal productivity			Fertilizer level (kg ha^{-1})	
	Weed	Soil	Drainage	Crop		F. manure	Fertilizer	Irrigation	F. manure	Fertilizer	Irrigation	Optimum	Actual
1	0	0	1	0	16	0.078	0.090	0.040	42.1	2.1	35.2	67	76
2	0	0	1	1	51	0.032	0.098	0.020	23.4	2.1	30.6	112	95
3	0	1	1	1	21	0.024	0.102	0.020	14.1	2.7	35.4	167	85
4	1	0	1	1	26	0.018	0.077	0.031	9.7	2.6	36.4	74	64
5	1	1	1	1	11	0.009	0.074	0.019	4.6	1.5	32.4	102	92
Weighted average					170	0.033	0.085	0.023	19.0	2.1	30.7	90	85

Weeding: 1 if the field was weeded, 0 if no weeding was done; Soil: 1 for heavy soils, 0 for light and medium soils; Drainage: 1 for good drainage, 0 for poor drainage fields; Crop: 1 for continuous rice–wheat, 0 for non-continuous rice–wheat; Frequency: number of observations.

Table 6
Production elasticities of qualitative variables under alternative environments in wheat production, Rupandehi, Nepal

Environment	Environment				Frequency	Elasticities				
	Weed	Soil	Drainage	Crop		Weed	Soil	Drainage	Crop	Manure
1	0	0	1	0	16	–	–	0.029	–	−0.18
2	0	0	1	1	51	–	–	0.254	0.054	−0.18
3	0	1	1	1	21	–	−0.007	0.193	−0.026	−0.18
4	1	0	1	1	26	0.703	–	0.283	−0.089	−0.18
5	1	1	1	1	11	−0.123	−0.265	0.139	−0.112	−0.18
Weighted average					170	0.080	−0.027	0.177	−0.033	−0.18

Weeding: 1 if the field was weeded, 0 if no weeding was done; Soil: 1 for heavy soils, 0 for light and medium soils; Drainage: 1 for good drainage, 0 for poor drainage fields; Crop: 1 for continuous rice–wheat, 0 for non-continuous rice–wheat; Manure: 1 for discontinuous farmyard manure application, 0 for continuous application; Frequency: number of observations.

ronment (Table 5). They were applying less than optimum fertilizer, except where conditions were ideal (good drainage, no weeding required or done, crop history non-continuous, and light soils). This may be due to the difficulty in understanding the input–output behavior under marginal environments.

Weeding increased production in all cases, except when rice–wheat were rotated on heavy soils with good drainage. It was not clear whether this was due to heavy weeds that damaged the crop before weeding under such conditions, or because some portion of the crop was harvested as fodder during weeding. Heavy soils significantly reduced wheat productivity, while good drainage significantly improved it (Table 6).

5.3. Long-term sustainability

The elasticities of the long-term practices reported in Table 6 show the percentage accumulated carryover effect of each practice compared with the base-run practice. Parcels under continuous rice–wheat rotation for more than 3 years had significantly lower production compared with parcels where rice–wheat was non-continuous under all environments, except where soil was light, had good

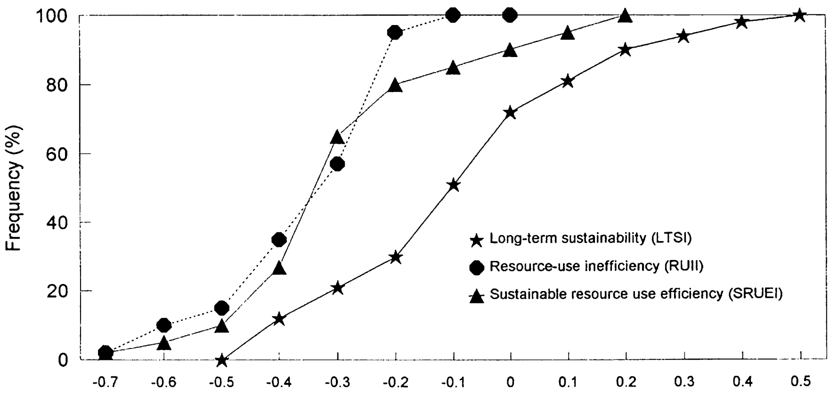

Fig. 1. Distribution of LTSI, RUII and SRUEI in wheat production, Rupandehi, Nepal. Note: resource-use efficiency values are plotted on a negative scale.

drainage, and the field had not to be weeded. The average decrease was more than 3%. The decrease was highest on marginal lands with poor drainage and heavy soils (not reported because of few observations), implying that continuous rice and wheat on fragile soil decreased productivity.

Similarly, discontinuity in farmyard manure application had a significant impact on productivity. The parcels where farmyard manure was not applied to every crop had about 18% lower productivity compared with parcels where manure was used for every crop under all environments.

The farm-specific LTSI was estimated using Eq. (6). This shows the accumulated marginal effect of all long-term management practices evaluated at the farm-specific levels of variable input and resource type. The LTSI estimated in this study may be partial in the sense that all the relevant long-term practices that affect sustainability might not have been included in the analysis.

About three-quarters of the farmers were found to have impaired the long-term sustainability of their parcels because they could not apply farmyard manure to each crop every year, and because they followed rotations inappropriate to the parcel conditions. About one-third of them had impaired sustainability to the extent that it reduced annual yield by more than 20%. Long-term practices did not affect sustainability on about one-quarter of the farms, and another one-fifth had improved long-term sustainability to the extent that it enhanced yield by more than 10% (Fig. 1).

5.4. Extent and determinants of resource-use efficiency

The RUII was estimated using Eq. (3). The frequency distribution of the indices is shown in Fig. 1. The average resource-use inefficiency in the sample was 25%. This implied that 25% higher production could be achieved without additional resources, or input use could be reduced to achieve the same output level. Only 6% of the farmers had resource-use inefficiency of less than 20%, while 69% of farmers had inefficiency of more than 30% (Fig. 1). These inefficiency estimates agree with those reported for wheat and other crops in other studies (average inefficiency from 12 studies reviewed in Ali and

Table 7
Determination of resource-use efficiency in wheat production, Rupandehi, Nepal

Variable	Variable explanation	Coefficient	SE	Contribution R^2
Farm management practices				47
Land preparation quality	1 = cloddy and fair; 0 = good	−0.0096 ***	0.0025	2
Crop stand variability	1 = quite variable; 0 = some, little	−0.0407	0.0423	5
Time of seeding	Deviation from 3rd week, Nov.	−0.0004	0.0007	3
Disease dummy	1 = with disease; 0 = without disease	−0.0394 *	0.0264	7
Rat damage	1 = severe; 0 = none, some, moderate	0.0324	0.0391	4
Plant population dummy	1 = poor and fair; 0 = good	−0.0582 ***	0.0230	13
Variety	0 = if variety is NL297; 1 = otherwise	−0.0768 **	0.0447	13
Socio-economic environment				53
Off-farm job	Family members working off-farm	−0.0362 ***	0.0167	12
Migration dummy	1 = indigenous; 0 = migrant from hills	−0.0391 *	0.0242	9
Family size	No. ha^{-1}	0.0032	0.0028	5
Machine dummy	1 = owns tractor; 0 = no tractor	0.0453	0.0401	5
No. of parcels	Number	−0.0008	0.0013	4
Farm size	ha	0.0078	0.0078	6
Plot accessibility dummy	1 = far; 0 = near	−0.0287 *	0.0211	7
Tenure	1 = owned; 0 = rented, tenant	0.0472	0.0459	5
Intercept		0.7631 ***	0.0553	
R^2		0.19		

Asterisks indicate significance: *** 1%; ** 10%; * 15%.

Byerlee (1991) was 30% but varied substantially from 10 to 50%).

It is worth noting that the RUII was estimated after controlling the effect of long-term management practices. The coefficient of correlation between the RUII and LTSI was 0.20, and found to be not significant at the 5% level, implying that different set of factors may be responsible for the two in the sample area. Adding the RUII (after converting it to negative values) and LTSI showed that only 5% of farms gained in productivity by up to 10% or more as a result of sustainable resource-use efficiency, while a productivity decline of at least 20% or more was observed on 80% of farms owing to the net balance of the short- and long-term effects of management practices.

To quantify the determinants of resource-use efficiency, the farm-specific indices were regressed against farm management practices and socio-economic factors as specified in Eq. (7).[3] The results are reported in Table 7.

The relative contributions of farm management practices and social factors were almost equal in determining the resource-use efficiency in wheat production of the sample farmers. Farm management practices that reduced resource-use efficiency significantly included poor plant population (5.8%), use of wheat varieties other than NL297 (7.6%), poor land preparation quality (1.0%), and disease incidence (3.9%). Surprisingly, the timing of wheat cultivation was not significant. Poor land preparation may also represent the effects of late wheat cultivation, because late cultivation implies hectic land preparation.[4]

Table 8
Determinants of farmyard manure application to wheat, Rupandehi, Nepal

	Coefficient	SE
Intercept	1.0584	1.2938
Standard animal units (SAU ha^{-1})	0.4590 ***	0.1347
Family size per SAU	−0.1462 *	0.1049
Source of fuel (1 if farmyard manure is the only source in dry season; 0 otherwise)	−0.6437 *	0.5128
Farm area (ha)	−0.1010	0.2180
Land type (0 if lowland; 1 otherwise)	3.0556 ***	0.9031
R^2	0.1386	

Asterisks indicate significance: *** 1%; * 15%.

Among socio-economic factors, farmers with off-farm jobs, parcels cultivated by indigenous farmers, and plots with poor accessibility had lower resource-use efficiency. The coefficients of these variables were significant at least at the 15% level, and a significant proportion of variability in resource-use efficiency across farms was explained by these variables. Farms owned by local farmers produced 3.9% less than farms owned by migrants, and poor accessibility of land parcels reduced efficiency by 2.9% at the given level of input use. Farmers with off-farm jobs had 3.6% lower production than full-time farmers at the given level of input use. These results are in accordance with the findings of Ali and Flinn (1989) for Pakistan, but contradict Herdt and Mandac (1981) for the Philippines. The coefficients for family size, farm size, tenancy, machinery ownership, and number of parcels were not significant.

5.5. *The determinants and consequences of low farm-based nutrient recycling*

Estimates of the determinants of farm-produced farmyard manure application to wheat crop as elaborated in Eq. (8) are reported in Table 8. One more SAU increased the farmyard manure availability for

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[3] The two-step approach used in this study (first estimating resource-use efficiencies and then regressing them on socio-economic factors) has been challenged by some authors in favor of the one-step approach (i.e. direct or non-frontier approach) where socio-economic variables are included in the production function (Muller, 1974; Battese et al., 1989). The non-frontier approach has the advantage of allowing estimation of the interaction between physical input and socio-economic variables, which are inseparable in production. Ray (1988) preferred the two-step procedure when the production function is multiplicatively separable from what he calls discretionary and non-discretionary inputs. Ali and Byerlee (1991) and Kalirajan (1991) preferred the two-step approach to avoid the simultaneity problem most commonly present owing to multicollinearity between physical inputs and socio-economic variables.

[4] The R^2 of the estimation is very low, although some of the variables included in the estimation are significant. This may be due to the presence of many other socio-economic variables related to resource-use efficiency, but missed from our analysis.

wheat at a rate of about 0.5 t ha^{-1}. One more adult family member per animal unit diverted farmyard manure towards home consumption, and reduced farmyard manure availability for wheat production at the rate of 0.15 t ha^{-1}. A farmer who did not have other sources of fuel had about 0.6 t ha^{-1} less farmyard manure for wheat production, compared with farmers who had other sources.

The number of animals per hectare of crop in Nepal has dropped from 3.86 in 1984–1985 to 3.43 in 1988–1989, mainly because of lower fodder availability and expanded cultivation on marginal lands. This implies farmyard manure supply for wheat has dropped by about 0.25 t ha^{-1}. These results agree with the monitoring survey results, in which about 66% farmers reported that less farmyard manure was available for crop production (Giri et al., 1993), and the observations of other studies (Cruz and Gibbs, 1990).

The consequences of the lower farmyard manure supply can be seen by estimating the marginal rate of substitution between manure and fertilizer. The marginal rate of technical substitution depends upon the type of soil, drainage conditions, crop history, etc. and the level of other input use. On average, it was found that a 1 t reduction in farmyard manure would require 9.5 kg additional fertilizer to compensate the loss of output.

Using the above marginal rate of substitution, the implication of reduced farmyard manure supply in 4 years was estimated to require about 3 kg ha^{-1} more fertilizer to produce the same level of output. This did not include the effect of shrinking sources of firewood, which would further increase the dependency of farmers on farmyard manure for fuel, and therefore reduce its availability for wheat production. These figures are only indicative of the direction in which agriculture in Nepal could accelerate in the near future, if growth in crop production is not integrated with livestock and forestry sectors and population planning.

6. Summary and policy implications

This study develops a theoretical framework to quantify the socio-economic determinants of three aspects of sustainability: resource quality as affected by long-term practices (i.e. control variables), resource-use efficiency, and domestic soil nutrient cycling from farmyard manure. The model was applied to wheat cultivation in Nepal.

To estimate the determinants of sustainability, I proposed to monitor small parcels with respect to long-run management practices in retrospect. The carry-over effect of these practices on resource quality can then be estimated by including different options of these practices as explanatory variables in the production function, and taking its partial derivative with respect to these practices. Long-term sustainability indices can be developed by taking the total derivatives of the production function with respect to these practices, and evaluating it at the farm-specific input use and resource type. Two such practices chosen in the wheat cultivation in the Tarai of Nepal were crop rotation history and continuity of farmyard manure application, although any number of long-term management practices can be included.

The main empirical finding of the study is that continuous long-term management practices do affect the sustainability of crop production. For example, continuous rice–wheat rotation in fragile environments (heavy soils and poor drainage) and discontinuous farmyard manure application reduced the quality of resources, resulting in less productivity. More studies on the physio-chemical nature of the changes in the soil under continuous rice–wheat rotation are needed. Alternatives to continuous rice–wheat rotation and farmyard manure application, e.g. grain legumes as a catch crop in rice–wheat rotation, should be explored. Farmyard manure handling practices should be studied to prevent losses and enhance the effectiveness of its application.

Farmyard manure availability in the area declined because of the decrease in animal units per hectare, population pressure per unit of animal, and increased use of manure for fuel. This decline in farm-based nutrient cycling had implications for the use of fossil-based inputs. For example, 1 t less farmyard manure would require an additional of 9.5 kg of fertilizer to maintain the same production level. Developments in agriculture, therefore, must be linked to population planning, livestock, and forestry development.

There was substantial scope to improve productivity at the existing level of inputs and resources.

Gains in output from improvement in efficiency are important where opportunities to increase production by bringing additional virgin lands into cultivation have significantly diminished, while at the same time population pressure has increased (Bravo-Ureta and Evenson, 1994), as is the case in Nepal.

Resource-use efficiency was affected by the poor plant population, planting varieties other than NL297, disease incidence, and substandard land preparation quality. Farm management practices in general have been neglected in sustainability research. Research and extension programs that improve the quality of farm management practices will advance the productivity and sustainability of the system.

Socio-economic factors influencing resource-use efficiency in wheat production in the area included farmers' engagement in off-farm jobs, their migration status (indigenous or migrated), and plot inaccessibility. One reason for the differences in efficiency across social groups may be differences in dependence on agriculture for a livelihood, as an off-farm job may more than compensate for the loss in efficiency incurred.

These findings are particular for wheat only. A similar analysis for the other component of the rice–wheat system (i.e. rice) is needed. A better measure of soil type, and inclusion of more long-term farm management practices would improve the analysis.

Acknowledgements

I am grateful to the rice–wheat team in Nepal, especially of Dr. Peter Hobbs, Dr. Harrington, and Mr. Giri for allowing me to use the rice–wheat monitoring survey data in Nepal. The helpful comments on the earlier draft by Drs. P.L. Pingali, S. Fujisaka, S. Pandey, M. Hussain, P. Hobbs, D. Byerlee, and anonymous referees are acknowledged. The help of Ludhi Velasco in computer analysis is highly appreciated.

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