Environment and Development Economics 4 (1999): 333–356

Tanzania's soil wealth

KJELL ARNE BREKKE
Statistics Norway, Research Department, P.O. Box 8131, Dep. N-0033 Oslo, E-mail: kjell.arne.brekke@ssb.no

VEGARD IVERSEN
Wolfson College, Cambridge, CB3 9BB, U.K., E-mail: vi201@econ.cam.ac.uk

JENS B. AUNE
Centre for International Environment and Development Studies, NORAGRIC Agricultural University of Norway, N-1432 Ås-NLH. E-mail: jens.aune@nlh10.nlh.no

ABSTRACT. This paper adopts soil scientific models of soil productivity and degradation in Tanzania into an intertemporal optimisation framework. The farmers choose labour input, capital investment and fertiliser input to maximise soil wealth, i.e., the present value of soil rent. First we focus exclusively on soil mining, considering the nutrient stocks as determinants of land productivity. Next, we focus on soil erosion, and include rooting depth as determinant of land productivity. We compute the soil wealth under the assumption that the opportunity cost of labour is equal to current wages, or alternatively equal to zero. Our estimates suggest that the potential gains from change in agricultural management are considerable. Moreover, the shadow price on root depth and hence the returns to land conservation investments are highly sensitive to our labour market assumptions. We also find that the value of the eroded soil amounts to 12–17 per cent of the value of Hicksian income, and the savings required to maintain consumption amounts to 13–29 per cent of the contribution to GDP.

1. Introduction

Soil erosion and soil-mining (extraction of nutrients exceeding replacement rates) represent threats to the long-run potential of agricultural production in sub-Saharan Africa. In Tanzania, agriculture accounts for more than 60 per cent of GDP and of merchandise exports. The potential consequences of land productivity declines are further exacerbated by the fact that 84 per cent of the population depend on land for employment and livelihood security. Tanzania is among the African countries with the highest rates of nutrient losses, with average annual losses of nitrogen in

Acknowledgements: We wish to thank the Norwegian Research Council, through the Economy and Ecology Programme for providing the financial support to this project. Helpful comments were received from Knut Alfsen, Sverre Grepperud, Karine Nyborg, Haakon Vennemo, Ragnar Øygard and from the associate editor and three anonymous referees.

the order of 20 kg per ha (Stoorvogel and Smaling, 1990). Removal of nutrients through the harvested product and through soil erosion are the major contributors to this net loss. Land degradation has thus been identified as an acute environmental problem in Tanzania (World Bank, 1996). Analysis of national income from agricultural production should account for this depreciation of natural capital, and this study makes an effort to quantify the on-site effects of land degradation on national income in Tanzania.

Erosion and soil-mining have been common on land cultivated by smallholders. This can partly be attributed to domestic agricultural policies that up to the mid 1980s discriminated against rural households by suppressing producer prices and maintaining government control over agricultural marketing institutions.[1] Simultaneously, agricultural inputs were rationed and subsidised fertiliser application mainly confined to maize producers in the Southern Highlands, supporting national self-sufficiency in the staple in the Tanzanian diet. The gradual policy shift under the umbrella of the New Economic Recovery Programme commencing in 1986 and still ongoing, has significantly altered incentives towards agricultural producers with regard to pricing and marketing of output, and with regard to access to and pricing of inputs. For fertilisers, an important nutrient source, removal of subsidies combined with sequential devaluations, increased the price paid by farmers by an average of 85 per cent in 1991/2 (Sankhayan, 1995). Towards the end of 1992, the total volume of fertiliser consumption had not responded significantly to these changes, leaving the average fertiliser application in Tanzania at 14 kg per ha of arable land. The corresponding figures for Kenya and Zimbabwe were 41 and 48 kg, respectively (FAO, 1994; UN, 1996).

In this paper we study the cost of soil degradation in a model combining economics and soil science. Using such an approach in a CGE framework, Franco *et al*. (1993) estimate a 1.3 percentage point decline in economic growth from land degradation in Nicaragua. In a more recent study of Ghana, offering a better description of the linkages between land degradation and productivity declines, the corresponding figure is 0.3 percentage points (Alfsen *et al*., 1995). Bojø (1996) has surveyed studies estimating the national costs of land degradation for sub-Saharan African countries. Conspicuous among these, Sutcliffe's (1993) work on Ethiopian data relates productivity declines to erosion estimates based on the Universal Soil Loss Equation (USLE), and combines a soil-life model with a Water Requirement Satisfaction Index. In addition, the study calculates the impacts on productivity of breaches in the nutrient cycle to determine the costs of nutrient extraction.

A noteworthy shortcoming in efforts to quantify the costs of land degradation is the absence of a theory of optimal resource management, which makes theoretically consistent estimation difficult. In this paper we try to deal with this shortcoming in an intertemporal optimisation framework. As land degradation is a long-run problem, we believe the intertemporal perspective to be important. This allows us to consider soil in a resource extraction perspective. Using a credible soil-scientific foundation, we find

---

[1] The 'urban bias' hypothesis proposed by Bates (1981).

that for many crops and areas, fertilisers are underutilised. One point frequently overlooked and often misrepresented in the economic literature on land degradation, is that increased crop output per hectare through crop canopy reduces soil erosion. This strengthens the above conclusion.

To simplify, cultivated area and the crop choice will be exogenous and constant throughout our simulations. We thus disregard the optimal crop choice studied by Burt (1981). This would be unrealistic, because farmers have options in deciding which crops to cultivate. Especially, the model will not take into account that farmers may respond to erosion by shifting to other crops. Relaxing this assumption is beyond the scope of this paper. It would be too information intensive because areas used for production of cassava today are not necessarily suited for production of maize or coffee tomorrow. Hence, we would need to know much more about the agro-ecological conditions in different areas. This would also make the model much more complicated.

Present policy debates often centre around incentives at the micro-level, and there is a rich literature on how institutions, financial incentives, and absent or thin markets influence the resource allocation decisions of farming households.[2] Our study attempts to quantify the cost of land degradation from a national perspective, indicating substantial costs and huge potential improvements. To understand why these potential benefits are not realised, analyses of incentives at the micro-level are required. The national perspective is not intended to substitute for these microeconomic insights. Rather, the optimal management regime in our model provides a point of reference against which the current performance of the agricultural sector may be evaluated.

One more important point deserves mention. Initially, we assume that the government's objective is to maximise soil wealth, and that there is alternative demand for labour at given wages. The simulations then recommend substantial reductions in labour input in agricultural production, which is not very realistic even in the long run. In Section 5 we develop a version of the model with fixed labour input to account for the important role of the agricultural sector for employment provision. We find our labour market assumptions to impinge strongly on the shadow price of land and hence on returns to land conservation investments.

2. Land degradation as a resource management problem

It is instructive to start off applying resource management terminology to the central concepts in this paper, soil mining and soil erosion. As may be well known, a stock of renewable resources will recover unless threshold values are violated, while reduction in a stock of exhaustible resources is irreversible over a reasonable time horizon. Barbar (1986) suggests that soil quality decline belongs somewhere between these categories, and classifies land or soil as slowly renewable resources.

A more precise definition may, however, be arrived at. When the major reason for land degradation is nutrient loss, soil quality can improve from supply of manure or fertilisers or from investment in soil-improving measures that secure a continuous flow of nutrients to the relevant land

---

[2] See Grepperud (1995) for a review of this literature.

plot. Agroforestry systems typically have this property. Similarly, the most common traditional response to soil fertility declines in African farming systems is to allow nutrient stocks to rebuild by leaving land fallow for a suitable period of time. Over a short time horizon, this regeneration capacity refers exclusively to the nutrient stock dimension of soil quality. Net-extraction of nutrients or soil mining can thus occur and drastically affect land productivity without posing an irreversible long-run threat to land productivity since measures are available not only to arrest, but also to compensate for nutrient losses *ex-post*.

Topsoil and soil physical structures, on the other hand, are best described as slowly renewable resources. Over a reasonable time horizon, erosion induced losses of topsoil and damage to soil-physical structures are irreversible. This property gives the problem a more serious flavour. Pure declines in nutrient stocks, and losses of topsoil and soil-physical structures are therefore parallels to the distinction between renewable and exhaustible resources.

In the first two model versions, the soil mining model, land productivity (soil quality) is a function of nutrient stocks. This stock will change if nutrients are added, when nutrients are extracted through the crop, or when nutrients are lost (or rather transported and deposited) because of soil erosion. A simplified description of the nitrogen cycle in soils will be used to illustrate the dynamics of soil fertility. This model has its strength when soil erosion represents less of a threat to soil-physical properties, and shortage of and declines in nutrient stocks is the main constraint on land productivity. The model will be used to derive empirical wealth estimates in Section 4 of the paper.

To enrich the discussion and depict other important aspects of land degradation problems, it is necessary to reformulate the model to entail a two-dimensional description of soil-quality. Apart from nutrient extraction, the model in Section 5 will capture the negative effects of erosion on rooting depth, i.e., the depth of soil that crop roots are able to utilise for extraction of nutrients and water. Unlike nutrient extraction, root depth reductions are irreversible.

3. The soil-mining model

To model soil mining, we assume that production on a hectare (ha) of arable land can be described by a Cobb–Douglas production function

$$Q_t = f(K_t, L_t, N_t) = AK_t^{\alpha_K} L_t^{\alpha_L} N_t^{\alpha_N} \tag{1}$$

where K_t is capital input, L_t is labour input and N_t denotes the nutrient content of the soil. Access to land is assumed to be fixed, and we hence assume decreasing returns to scale in the production function. The dynamics of real capital is

$$\dot{K}_t = I_t - \delta K_t \tag{2}$$

where I_t is investment and δK_t denotes depreciation of the capital stock in year t. Soil quality and land productivity is a function of the nutrient stock. In a simplified form, the dynamics of this nutrient stock can be described as

$$\dot{N}_t = F_t - Q_t n - \beta E_t \tag{3}$$

where F_t is the input of nutrients from a nutrient source applied by the farmer in the form of organic or chemical fertilisers. More generally, F_t could include nutrient flows from agroforestry systems or natural regeneration from fallow. n is the unit content of nutrients extracted through the cultivated crop and βE_t is the loss of nutrients through soil erosion. Equation (3) reflects the most important variables in the nitrogen cycle, but provides a simplified description of nitrogen flows.

The magnitude of erosion on cultivated land depends on variables such as rainfall, crop variety, yield, land slope, soil type and soil conservation measures. In flat terrain, other than under arid conditions, soil erosion will not contribute much to nutrient losses. The soil-mining model will thus be relevant when the linkage between land productivity and nutrient losses are not complicated by negative effects of erosion on soil physical structures.

According to the Soil Loss Estimation Model for Southern Africa (SLEMSA), developed by Elwell and Stocking (1982), crop canopy is an important determinant of the magnitude of erosion. Since increased canopy reduces the kinetic energy with which raindrops hit the ground, the damage to soil from rainfall is reduced. Surging yields also increase the binding capacity of the root system of the crop, which makes the soil less susceptible to erosion.

Root structures and protective plant cover vary between crops. This is also the case for the linkage between yields and crop canopy. To illustrate the significance of canopy for erosion rates and land degradation, consider the case of maize, the most important and area-consuming crop in Tanzania's agricultural sector. Different authors report annual soil losses on cultivated land in Tanzania in the range of 6 to 52 tons per ha (Aune, 1995). This large variation is due to differences in local management and to differences with regard to rainfall characteristics, soil type and land slopes. For a conservative estimate of 15 tons per ha (equivalent to 1.5 mm per ha) a surge in yield for an average maize farm from the low current to a feasible level of 2500 kgs could reduce annual erosion rates by 12–25 per cent, suggesting considerable prospects for environmental gains from more intensive agricultural cultivation. The point here is that low yields may accelerate erosion rates considerably.

Using SLEMSA, the amount of erosion can now be expressed as a function

$$E_t = \phi \cdot exp(-bQ_t). \tag{4}$$

The parameters ϕ and b in (4) depend on slope, rainfall intensity and other variables that are unique to each crop. In the following, we shall assume that these are constant and crop specific. According to (4), smallholders can manipulate erosion rates by changing the cultivated crop, or by influencing yields via the control variable in the optimisation problem, nutrient inputs through fertilisers. In this model, therefore, soil erosion decreases with yields and hence with increased production. In real life, this is not necessarily the case, since output may be increased by expanding the cultivated area. Our model hence removes two important options from the decision making of farming households: the decision about which crop to grow, and whether to reduce or expand the cultivated area. Expansion of cultivated area normally implies more erosion since forests and grasslands provide a better protection than crops for the soil. Keeping these variables exogenous allows us to focus more sharply on the yield–erosion linkage.

Investments in soil conservation measures such as terracing will not be considered explicitly in the analysis. It should, however, be observed that the following analysis which establishes shadow prices on root depth under different assumptions, is a prerequisite for economic analysis of conservation investments, and illustrates the sensitivity of the returns to such investments to the underlying assumptions.

Linking nutrient stocks and productivity declines

Equation (3) describes the net loss of nutrients, and through (1) this loss is translated into productivity declines. Let w_K, w_L and w_F denote the factor prices of investment goods, labour and fertilisers in the wealth maximisation problem

$$max \int_0^\infty (P_t Q_t - w_F F_t - w_L L_t - w_K I_t) e^{-rt}\, dt. \tag{5}$$

To simplify, we introduce the net price of the product. Let

$$\gamma = -\frac{\partial E(Q)}{\partial Q} = b\phi \exp(-bQ),$$

be the marginal effect on erosion from a marginal increase in crop yield. Since the crop sells at market prices P, and will remove $n - \beta\gamma$ units of nutrients from the soil, at a shadow value υ, the net price will be $p = P - \upsilon\ (n - \beta\gamma)$. As shown in the appendix, the first-order conditions for optimal inputs of investments, labour and nutrients can be written as

$$\begin{aligned} \alpha_K pQ &= (r + \delta) w_K K \\ \alpha_L pQ &= w_L L \\ \alpha_N pQ &= r w_F N. \end{aligned} \tag{6}$$

This is the usual fixed cost–share solution with Cobb–Douglas technology, where $(r + \delta)w_K K$ is the user cost of capital, $w_L L$ is the labour cost and $rw_F N$ is the user cost of the nutrient capital. Note that the optimal capital stock and especially the optimal stock of nutrients are sensitive to the choice of interest rate r. For given Q, doubling the interest rate would reduce the optimal nutrients stock by 50 per cent, but as this would also reduce Q, the total effect on N is even larger. In the main simulations in this paper, modest interest rates in the range of 4–5 per cent will be used. This is far from the very high interest rates facing poor farmers reported in Holden *et al.* (1998), but close to the interest rates in international credit markets. We return to this issue in Section 5, and include some sensitivity analyses.

Combining the first-order conditions with the production function gives us four equations to determine Q_t, L_t, N_t and K_t. These first-order conditions uniquely determine the state variables. Since the model is linear in investments in both real capital and nutrient stock, the optimal solution is to immediately adjust to the optimal levels of soil quality and capital input, and apply the corresponding labour input. To see this, note that if the shadow price on capital is higher than the investment cost w_K, it is optimal to increase the investment rate. Hence, investments are infinite until the optimal capital stock is attained.

A caveat is in place here. The model allows for negative investment. This may be unreasonable even for real capital, but is clearly unrealistic for nutrient stocks. In most cases, the optimal nutrient stock is higher than the current level, and when this is not the case, the immediate adjustment should be considered as an approximation of the case with a more gradual adjustment process. We expect that soil quality in most cases is below the optimal level and external inputs can then be used to adjust the levels of nutrient stocks. According to our model, this adjustment can take place instantaneously. In real life, however, nutrient stocks may be built up only gradually. This implies that by using fertiliser prices and instant adjustment, our model overestimates output over the first few years. In addition, alternative sources of nutrient supplies to boost nutrient stocks should be examined to compare the cost effectiveness of these with fertilisers.

Now, let π_t denote the net profit at the optimum

$$\pi_t = P_t Q^*_t - w_K I^*_t - w_L L^*_t - w_F F^*_t, \tag{7}$$

where $F^*_t = \dot{N}^*_t + Q^*_t\, n + bE(Q^*_t)$. The optimal nutrient input hence offsets losses to maintain the optimal nutrient stock, once it is established. A marginal increase in yields will now have two opposite effects; it increases nutrient mining and reduces erosion. Profit can be decomposed as a normal return to capital $(r + \delta)K_t$, and the scarcity rent on land $\pi_t - (r + \delta)\, K_t$. The total soil wealth is defined as the net present value of the scarcity rent minus the initial investments in soil quality, $w_F(N^*_0 - N_0)$. The initial adjustments reflect jumps in the state variables, and have to be accounted for separately. After a simplification, the soil wealth can be rewritten as

$$W = \int_0^\infty \pi_t e^{-rt}\, dt - w_K K_0^* - w_F(N_0^* - N_0). \tag{8}$$

If all prices are constant, the optimal production and factor use will be constant too. In this case, profit is constant and equal to

$$\pi_t = \pi = PQ^* - w_F(Q^* n + \beta E(Q^*)) - w_L L^* - w_K \delta K^*, \tag{9}$$

where $(Q^* n + \beta E(Q^*))$ is the amount of external nutrient supply required to keep N constant. The expression for soil wealth now simplifies to

$$W = \frac{\pi}{r} + w_F(N_0 - N^*) - w_K K^*, \tag{10}$$

where the first term is the present value of future profit. The second term is the value of excess soil quality—most likely negative—and the last term is the initial investment including a capitalisation of future returns to existing capital.

4. Empirical estimation of soil wealth

Model calibration

The agricultural policies of the Tanzanian government complicates the standard procedure for calibration of the elasticities α_i, and base year quantities to calibrate the constant A. This procedure would produce biased estimates since inputs use has been rationed, and hence inputs deviate from their optimal levels.

An alternative approach is to calibrate the output elasticity of nutrients from soil data based on soil scientific experiments. An exponential yield function calibrated using data from sub-humid regions of Africa (Aune and Lal, 1995) is given by

$$Q_t = Q_0[exp((F - nQ - E)tk) + X(1 - exp((F - nQ - E)tk))], \qquad (11)$$

where Q_t is yield in year t and F is the nitrogen quantity added through organic and inorganic fertilisers. As before, nQ is nitrogen extraction through the harvested crop. E represents half the loss of nitrogen from soil erosion. Only the soil organic nitrogen pools that are able to supply N in a relatively shorter time perspective, i.e., with turnover time less than 40 years, are taken into account here. As in Parton *et al*. (1987), we assume that these fractions represent about 50 per cent of the total soil. Moreover, k is a calibrating parameter and X accounts for differences between crops in their susceptibility to soil erosion, soil buffer capacity and water regime.

If $F - nQ - E$ is constant over time, soil quality can be expressed as $N_t = N_0 + t(F - nQ - E)$. Under this assumption, (11) can be rewritten as a function of N_t, and the calculator can be used to determine reasonable intervals for the output elasticity of nutrients.

For the major farming systems in Tanzania, data on nutrient extraction are obtained from Stoorvogel and Smaling (1990), and modified by crop using the factor for soil cover in the Universal Soil Loss Equation (USLE). Productivity declines for maize are assumed to be 50 per cent lower on a soil with high buffer capacity, since agroforestry experiments on maize suggest that yield declines are less pronounced on volcanic soils typical for the Kilimanjaro area (Kamasho, 1995).

Generally, perennial crops are less susceptible to soil erosion because of their deeper rooting systems, which enables trees to extract water and nutrients from a larger soil volume than annual crops. Based on the PI-models description of the link between rooting system and susceptibility to soil erosion (Pierce *et al*. 1983), it follows that trees will be less susceptible to the effect of erosion on yield. Legumes such as beans belong somewhere between annual and perennial crops due to a combination of nitrogen fixing capability and a shorter growing cycle. In our calculations, annual crops are tentatively set to be twice as susceptible to erosion as trees.

From (10) calculation of soil wealth requires calibration of the initial level of soil quality. Estimates of the net extraction of nutrients from soil in the major farming systems in Tanzania are derived by Stoorvogel and

Smaling (1990). Similarly, the annual (relative) loss of productive capacity on a hectare of land, denoted ϵ can be derived from (11). Formally, $\epsilon = \alpha_N \rho$, where $\rho = \frac{\dot{N}}{N}$. Thus

$$N_t = \frac{\alpha_N}{\epsilon}\,\dot{N}_t = \frac{\alpha_N}{\epsilon}\,(F_t - Q_t n - \beta E_t), \tag{12}$$

and equation (12) is used to calibrate N_0.

The agricultural sector

With the assumptions of exogenous crop choice and cultivated areas, the model allows us to study land areas of a specific quality with cultivation of one particular crop. The wealth for each crop variety and area is separately computed, and the national soil wealth is the aggregated wealth for all hectares of cultivated land. The soil wealth, clearly, will take on different values contingent on the crops grown. Hence, the optimal crop combination is the combination that maximises national wealth. With exogenous crop choices, the wealth estimates are based on the assumption that the same crops are cultivated on the same land areas. To arrive at a wealth estimate, the total outputs and estimates of areas under each crop for the agricultural season 1990/1 presented in Table 1 are used as model inputs.

Soil properties, labour allocations, fertilisers and other material inputs

Table 1. *Key figures in agricultural production in Tanzania 1990/1*

	Yield, tones	*Area, ha*	*Price, US$ per tonne*
Maize	2.111.000	1.848.300	120
Farming system			
Southern Highlands	944.553	551.947	
w/beans	252.794	208.075	250
Other	913.471	1.088.277	
Cassava	1.777.000	632.000	180
Sorghum	591.000	475.900	106
Beans	311.000	560.000	300
Paddy	370.000	310.400	200
Coffee	58.000	242.060	
Farming system			
Arabica w/bananas	26.146	87.600	1.280
Arabica	15.589	64.300	
Robusta	13.624	90.000	730
Tobacco	16.447	31.480	
Farming system			
Flue cured (large scale)	1.126	1.251	2.340
Flue cured (small scale)	9.592	16.488	
Fire cured	5.728	13.736	1.810
Cotton	261.900	424.860	500
Farming system			
Oxen	52.357	145.000	
Typical hand	9.321	29.000	
Improved hand	30.241	57.900	
Improved hand plus hired labour	169.979	193.000	
Tea	16.000	12.500	1300

Table 2. *Input structure, yields and productivity declines in farming systems in Tanzania in 1990/1 (per ha)*

				Nitrogen extraction (kg)			
	Capital stock (TZS)	*Labour (Mandays)*	*Yield (kg)*	*Crop*	*Erosion*	*Fertiliser (kg)*	*Annual prod. decline (per cent)*
Maize							
Southern Highlands	207800	136	2000	48.8	10.0	50 (SA)	1.3
w/beans	238440	132		24.4	7.5	25 (SA)	1.3
Other	162120	76		19.5	10.0	10 (U)	2.0
Cassava	15080	120	2800	30.8	5.0	0	0.6
Sorghum	20960	193	1250	35.0	10.0	0	3.0
Beans	138540	120	555	17.0	5.0	20 (SA)	3.0
Paddy	83300	217	1200	26.0	0.0	0	0.6
Coffee							
Arabica w/bananas	448000	184	297	11.7	2.5	20 (NPK)	0.7
Arabica	892940	183	242	9.5	4.0	20 (NPK)	0.6
Robusta	277660	128	151	6.0	4.0	0	
Tobacco							
Flue cured LS	1184540	536	900	50.3	7.5	650 (NPK)	0.2
Flue cured SS	1067280	533	581	32.5	7.5	650 (NPK)	0.2
Fire cured	717820	428	417	23.3	7.5	250 (SA)	
Cotton							
Oxen	289500	136	361	21.2	6.5	0	2.6
Typical hand	243500	132	321	18.7	6.5	0	
Improved hand	263300	138	522	19.6	6.5	30 (SA)	
TH + IH	350300	126	880	45.2	6.5	30 (SA)	1.1
Tea	115000	178	1200	42.0	4.0	30 (NPK)	0.9

show systematic and unsystematic variation across the countryside in rural Tanzania. Table 2 portrays the major farming systems in Tanzania together with estimates for inputs of labour, capital (in Tanzanian Shillings) and different types of fertilisers per ha of cultivated land. The table includes three different farming systems for maize cultivation: maize cultivation in the Southern Highlands, maize cultivation in combination with beans and sole-standing maize cultivated elsewhere. Similarly, three farming systems of coffee and tobacco and four systems of cotton cultivation are included. From yield figures, extraction of nitrogen through the harvested crop and erosion can be derived. The last column depicts the annual productivity declines in the farming systems derived from equation (15).

The figures in Tables 1 and 2 are based on official and other Tanzanian sources. For all crops, 1990/1 is the base year and the production figures

Table 3. *Output elasticities for three scenario alternatives*

	α_K	α_{L}	α_{N}
Alt. 1	0.15	0.15	0.15
Alt. 2	0.20	0.20	0.20
Alt. 3	0.15	0.12	0.25

Table 4. *Optimal quantity for each farming system in three scenarios, tonnes*

	Current Q	*Q*(1)*	*Q*(2)*	*Q*(3)*
Maize				
Southern Highlands	944.543	324.964	205.760	354.028
w/Beans	252.974	137.276	127.496	185.425
Other	913.741	374.213	276.446	534.733
Cassava	1.777.000	2.339.231	3.311.226	2.294.190
Sorghum	591.000	342.801	306.167	377.645
Beans	311.000	176.231	169.905	284.969
Paddy	370.000	420.825	722.277	1.150.772
Coffee				
Arabica w/bananas	26.145	14.378	13.565	22.500
Arabica	15.589	5.849	3.984	7.836
Robusta	13.624	3.868	2.090	4.565
Tobacco				
Flue cured LS	1.126	1.156	1.820	2.183
Flue cured SS	9.592	7.086	8.4872.559	11.903
Fire cured	5.278	3.098		4.524
Cotton				
Oxen	52.357	23.141	18.332	35.526
Typical hand	9.321	4.257	3.415	6.680
Improved hand	30.241	13.886	11.137	17.584
TH + IH	169.979	96.663	93.049	121.619
Tea	16.000	30.052	82.560	54.981

are obtained from van den Brienk (1992).[3] The input vectors are based on annual crop-wise reports published by the Marketing Development Bureau in Dar es Salaam. Area, input and output figures are based on estimates and data sources that partly contradict each other. The ambiguity of data from the agricultural sector in Tanzania is a chronic problem that unfortunately is not too uncommon in developing countries. This, of course, weakens the basis for making very strong conclusions.

The output elasticities for crops in the different farming systems used as inputs to derive the optimal quantities for different crops are depicted in Table 3. Crops like cassava and sorghum have low response to increased fertiliser input and the output elasticity for nitrogen for these crops will therefore be close to zero. For these two crops α_N is hence set equal to 0.01. Output elasticities for labour and capital are based on Sankhayan (1994). Since these elasticities are quite small, we will check whether our conclusions are sensitive to these assumptions.

Soil wealth estimates

In Table 2 inputs other than fertilisers and labour have been classified as capital. This means that agrochemicals, typically an annual input, is inte-

[3] The area estimates are probably less accurate and several sources are referred to subsequently. These include Crop Monitoring and Early Warning Unit (1993). Ministry of Agriculture (MoA) (1992), and cropwise annual reviews published by Marketing Development Bureau. Source for all price data: World Bank and Government of Tanzania (1992), pp. 43–51 and FAO (1993), pp. 90–1 for sorghum and cassava.

grated in the capital concept. Table 2 depicts data on input use and production figures together with the net extraction of nutrients calculated from 'representative' levels of use of fertilisers, crops composition, yields and soil erosion. The last column indicates the expected annual productivity declines derived from equation (11).

Using the different output elasticities in the three scenarios from Table 3, we have derived the optimal quantities of production for the major food and export crops in Tanzania. The results of the calculations are reported in Table 4, where $Q^*(i)$ for $i = 1, ..., 3$ is the optimal quantity in each scenario. The results indicate the order of magnitude of the deviations between current and optimal production.

Soil wealth with current and optimal resource allocation

The benchmark value for the soil is calculated as the present value of future production under the assumption of a constant input mix. This implies that the use of labour, capital, material inputs and fertilisers maintain a constant proportion to output, and hence that farmers reduce their input proportionally to soil quality deteriorations.

Analyses of soil quality changes are quite complex because soil quality deterioration reduces yields and the extraction of nutrients, while erosion increases as crop canopy declines. Numerical simulation of the total effect is straightforward, but to make calculations of the effect of current policy more transparent, we assume that with an extension of the current resource management, the sum of the two effects makes relative productivity declines constant, in other words that $\rho = \dot{N}/N$ is constant. In that case, yields will decline at an annual rate $\alpha_N\rho$. With constant prices, the net present value of future production will then be

$$W_0 = \frac{P_0Q_0 - w_KI_0 - w_LL_0 - w_FF_0}{r + \alpha_N\rho} - w_KK_0. \tag{13}$$

We assume that the real rate of interest is 5 per cent. According to Table 2, the crop and region-specific annual productivity declines caused by soil erosion and soil mining are in the range 0.5–3.0 per cent. If we assume that the average annual decline is 1 per cent, the soil wealth becomes negative if production costs exceed 5/6 of the value of output. Table 4 reports the 1990/1 and optimal outputs for different farming systems.

The deviations between 1990/1 and the optimal levels are considerable in several farming systems. First, the table indicates that maize production in the three major production systems generated negative wealth in 1990/1. Maize production in the Southern Highlands should for instance come down significantly, while maize intercropped with beans should be reduced less. Apart from output declines, production should be restructured towards more fertiliser-intensive production with conspicuous declines in labour input. As can be seen, the optimal paddy output is well above the current level of 1.2 tons per ha. Cassava output should increase from 2.8 tons per ha to an optimal level of around 3.6 tons per ha. For other food crops, the calculations suggest small adjustments compared to the 1990/1-levels.

For export crops, the model recommends expansion of production of flue cured tobacco in both farming systems and a significant increase in tea production. This requires investments that may not be available to credit-constrained farmers. The input of capital in tea production in Table 2 is low compared to other crops; tea is also among the major consumers of fertilisers in Tanzania. We may therefore have underestimated the costs of intermediate inputs in tea production. For tobacco, nutrient extraction figures do not reflect that production of one ton of tobacco requires the equivalent of two hectares of miombo woodlands (Mascarenhas, 1991). Tobacco input prices hence do not correctly depict the social costs of tobacco production.

Cobb–Douglas technology may overestimate the input substitution possibilities and hence the flexibility of the above production systems. The above findings are sensitive to the underlying assumptions and to the data we have used. Labour has for instance been priced at the market wage rate. Changing the shadow price of labour may have significant bearings on our results, as will be demonstrated in section 5.

Using (13), existing practices and the current prices, Tanzania's soil wealth should equal US$2.9 billion. The value of the agricultural product in the 1991 Tanzanian GDP was US$1.5 billion. Besides the land rent, GDP includes the return to labour without subtracting for capital and nutrients depreciation. The estimate therefore indicates that these components account for a large share of the current GDP.

Calculation of the soil wealth using the optimal levels for each crop and the corresponding optimal input use, increases total wealth to US$13.1 billion. This is more than fourfold the benchmark value, and indicates that the economic gains from a more rational utilisation of Tanzania's land resources could be considerable. In a sensitivity analysis, we increased the capital elasticity by a factor of 1.25 and the labour elasticity by a factor of 1.5. This left our wealth estimate very close to unaltered.

The soil-mining model has nutrient stocks as the main determinant of land productivity. This description is reasonable and relevant for land areas and regions where soil fertility declines represent the major constraints on productivity, provided that erosion has negligible effects on soil-physical properties. While this may indeed be reasonable for significant areas or regions in a country, and thus provide the basis for a sound partial analysis of national soil wealth management, it is unlikely to hold for all land areas. When soil erosion does impinge on the soil layer as well, the soil-mining model will underestimate the costs of soil erosion and overestimate the national soil wealth.

5. Soil quality in the two-dimensional model

Model structure

As noted, the soil-mining model is not capable of portraying the dynamics of land degradation processes in areas where soil mining and soil erosion coexist. While erosion removes soil and hence nutrients, the most important effect of erosion is the removal of top soil and destruction of soil-physical structures. Unlike in the soil-mining model, supplying nutrients cannot reverse this process. Drawing on Aune and Lal (1995) we use a multiplicative soil quality index, $S_t = g_1(N_t)g_2(D_t)$, where N_t denotes the nutrient content and D_t denotes the root depth. Soil quality is interpreted as a productivity index and the production function is linear in S_t. The production function is now

$$Q_t = f(K_t,L_t,N_t,M_t,D_t) = K_t^{\alpha_K} L_t^{\alpha_L} N_t^{\alpha_N} M_t^{\alpha_M} g(D_t), \tag{14}$$

where M_t is material inputs. The development in nutrient content is the same as in (3), while development in root depth is

$$\dot{D}_t = - E_t = -\phi exp(-bQ_t) \tag{15}$$

The optimality conditions derived in the Appendix are

$$\begin{aligned} K_t &= \alpha_K pQ_t/(r + \delta) \\ L_t &= \alpha_L pQ_t/w_L \\ N_t &= \alpha_N pQ_t/rw_F \\ M_t &= \alpha_M pQ_t \end{aligned} \tag{16}$$

but where the net price on crop now is $p = P - nw_F - \gamma(w_F + \lambda)$ and λ_t is the shadow price on root depth. The dynamics of this shadow price is given as

$$\dot{\lambda}_t = \lambda_t - pQ_t \frac{g'(D_t)}{g(D_t)}. \tag{17}$$

Solving the model for a finite time horizon T, sufficiently long to provide a good approximation for the infinite horizon case and short enough to make the inequality $D_T \geq 0$ not strictly binding, we get $\lambda_T = 0$. We may then solve the model numerically, guessing on initial shadow prices, and iterate until λ_T converges to zero.

We will refer to the basic model presented above as the reference model. This version of the model presumes that at current wages there is alternative employment for the current agricultural labour force. To study the importance of this assumption, we contrast it to the other extreme where there is no alternative employment. We refer to this as the exogenous labour version of the model, and consider the labour supply to be exogenously given. The first-order condition for labour demand in (16) is now replaced by $L_t = L_0$. Except for this all other equations are as above.

In the reference version of the model we also assume that crop prices are fixed. As the root depth decreases, yields decline, and we would expect prices to increase. Especially if the root depth and yields are decreasing in other parts of Africa too, regional supply of these crops will decrease, and prices will increase. On the other hand, prices should not be expected to deviate too much from international market prices. To study this case, we run a simulation assuming a price elasticity of 0.4, i.e., where prices are given by $P_t = kQ_t^{-0.4}$. We refer to this as the endogenous price version of the model. Note that while the price depends on Q_t the price is still assumed to be exogenous to the individual farmer, hence intertemporal optimisation is undertaken, given the price path.

Finally, the optimal input mix may differ from what is currently observed. We do not go into details on institutional factors explaining this deviation, but to illustrate the long-run consequences of the current practice we run a simulation with constant input mix, i.e., with K_t/Q_t constant over time, and similar for all other inputs. This will be referred to as the benchmark. For all these alternative models, we compute the wealth, and the shadow price on root depth.

Note that with no alternative use of labour, we cannot really separate return to labour from resource rent. Hence, in this case we add soil wealth and present value of labour income. To be able to compare the results with those from the other versions of the model, we estimate a hypothetical soil wealth by computing the resource rent as if wages were adjusted to make $L_t = L_0$ optimal. To make the results from the other versions of the model comparable, we compute the present value of labour income in those cases, too. Note, however, that in some of the simulations, parts of the labour stock currently working in agriculture is transferred to other sectors, and as we want to include labour income from the total labour stock, these are included too.

Empirical results

To study the effects of the two-dimensional specification of soil quality, we focus on maize production in the Southern Highlands in Tanzania. The rooting depth in this area is assumed to be 30 cm for maize. When the root depth is less than 8.5 cm the soil becomes unproductive. The effective rooting depth is therefore the depth exceeding 8.5 cm. At the moment, erosion removes about 1.5 mm a year and the soil should hence remain productive for a period of 140 years. This prediction needs to be modified to account for the feedback effect, since a reduction in rooting depth lowers soil productivity, which reduces yields and crop canopy, and thus accelerates erosion. With the current input structure, the soil will remain productive for a period of about 110 years.

Another important observation is that while the first 11 cm of root depth losses will reduce productivity by 30 per cent, the next 10.5 cm lost will completely wipe out the productive capacity of the soil. Since the timespan before the first 11 cm are lost is about 70 years, the important consequences of soil erosion will become visible only in the last part of the simulation period.

We apply an interest rate of 4 per cent, as a risk-free rate on international credit markets, but also do some simulations with an interest rate of 8 per cent. Based on cost shares, we would estimate $\alpha_L = 0.649$, $\alpha_K = 0.004$, $\alpha_M = 0.155$ and $\alpha_N = 0.192$, which adds to 1.0, and constant return to scale. As there should be a return to land, this does not seem reasonable. Moreover, the soil scientific estimate indicates $\alpha_N = 0.3$. The elasticity of capital seems unreasonably low, and we have adjusted it to $\alpha_K = 0.05$. To leave some return to land, we reduce the two others to $\alpha_L = 0.3$, $\alpha_M = 0.1$. The elasticity of labour is then closer to the level reported in Sankhayan (1994). As an approximation to the index in Aune and Lal (1995), we get $g(D) = \sqrt{D}$

Table 5. *Summary of main results*

	W	$W + I$	P
Benchmark	267	3776	
Reference model	1123	1700 (+ 2921)	54
Exogenous labour	2431	4304	166
Endogenous price	1931	2933 (+ 2506)	123

Note: Wealth W and present value of labour income I in US$ per ha, numbers in parentheses are the value of labour made available for other sectors, P is shadow price on rooting depth in US$ per cm x ha.

For these assumptions, results are reported in Table 5, where W is the wealth in US$ per ha; the present value of future resource rent, and $W + I$ is wealth including the present value of future labour income. The numbers in parentheses reflect the present value of labour made available to other sectors when agricultural labour demand is below the benchmark level. Finally P is the shadow price of rooting depth in US$ per cm x ha.

The benchmark value is the present value of future land rent under the current management regime. This regime is defined by a constant input mix throughout the simulation period, with a proportional reduction in input quantities as the root depth declines. The soil wealth per hectare in the benchmark scenario is US$267.

If there is alternative employment or use of labour at the wage $1.22 per man day, and the farmers adopt optimal management, the wealth would increase to US$1,156. In this regime, a sharp reduction in labour input from 136 to 30 man days should be accompanied by a reduction in the nitrogen content of the soil from 1,950 kg per ha to 1,437 kg per ha. Notice that the model assumes that instant adjustment of N is possible, whereas in practice this would take time. Capital input should increase from US$24.5 to US$32.3 per ha. The production profile and root depth in this alternative are shown in Figure 1.

As in the previous calculations, the wealth-maximising yields for maize are significantly lower than the 1990/1 levels, and the average yield in the Southern Highlands should drop from 2.17 tons per ha to 1.13 tons per ha. This will increase erosion from 1.5 mm per year to 1.74 mm per year. This adjustment would make more labour available for other productive activities at the given wage rate. But, this shift can be optimal only if the redundant labour force can be gainfully employed elsewhere. The required scale of adjustment suggests that this may not be a very realistic assumption, even in the long run.

In this scenario, the initial shadow price of root depth is estimated to be US$54 per cm. The annual loss of 1.75 mm root depth is then valued at $9.5 per ha. This amounts to about 21 per cent of the return to wealth. Apart from the return on wealth, the contribution to national income includes the value of about 30 man days per ha. Under the optimal management regime, the annual cost of erosion corresponds to about 12 per cent of the total contribution to GDP.

We do not explicitly model the option to invest in measures that would

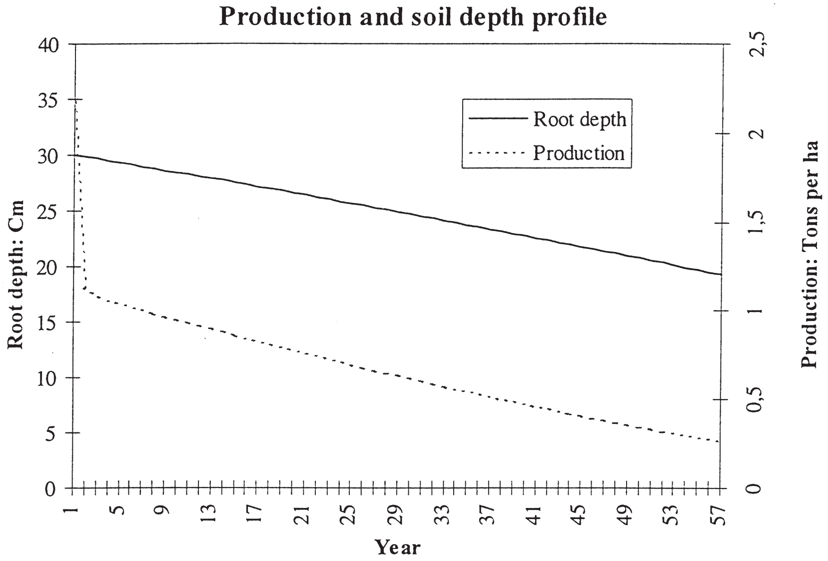

Figure 1. *The development of production and rooting depth in the reference scenario*

prevent soil erosion. But, the model can be used to estimate the value of such measures. Consider a measure that completely arrests erosion on one ha of land in the Southern Highlands. On this ha of land $E = 0$ for all yields. Reestimating the wealth under this assumption, we find that the wealth has increased by $771 per ha. Thus, if the investment cost of such a measure is less than $771 per ha, the project has a positive net present value.

The production profile and development of real rooting depth (D + 8.5 cm) along this solution is shown in Figure 1.

In the benchmark model, using the market wage as the shadow price on labour will overestimate the social costs of labour since the opportunity cost of labour will be close to zero when alternative employment opportunities are few. For the individual private landowner the labour cost will, however, equal the market wage. The deviation between private and social costs of labour drives down profits, the private value of land and the private returns to conservation investments.

Exogenous labour supply We note that in the reference model, the labour demand of 30 man days per ha is much below the 1990/1 levels of 136 man days, and it is unlikely that labour will find alternative employment at this wage rate. In an economy with few alternatives to agricultural employment, the relevant wealth concept can be redefined to include the value of human capital, i.e., the present value of future income to the labour force. An alternative objective is hence to maximise profit plus labour income taking the subsistence needs of the labour force into account.

If employment is fixed, it is not clear how to separate resource rent from return to labour. Valuing labour at the marginal productivity, wages would have to be lowered from US$1.2 to US$0.65 per man day and gradually decline, reaching US$0.45 per man day after 50 years. Using these wages, the wealth for maize production in the Southern Highlands increases to US$2,501 per ha, significantly above the previous estimate of US$1,156 per ha. The major reason for this increase in wealth is that wages are forced down.

The wealth-including present value of wages amounts to US$4,356 per ha which is up only US$580 from the benchmark, and actually the difference is less. The exogenous labour model assumes that labour demand is 136 man days per ha in all years, whereas in the benchmark the labour input declines with production. With current wages, the difference in present value is about US$800, more than the increase in $W + I$.

With exogenous labour input, the scale of production increases from the current level of 2.17 tons per ha to 2.63 tons per ha reducing erosion to 1.29 mm per year. The optimal content of nitrogen increases by about 1.5 tons per ha; from 1.95 tons per ha to 3.45 tons per ha. Note that the output elasticity for nutrient is a local approximation of the soil productivity index adapted from Aune and Lal (1995) and that with increases in N of this size, the marginal productivity is somewhat overstated.

The costs of labour for landowners are now driven closer to the social costs of labour, which in the absence of alternative employment opportunities remain close to zero. This increases profits, the shadow price of land and the returns to conservation investments. The incentives for land conservation move closer to the socially optimal, because the private costs of hiring labour move closer to the social costs, notwithstanding the perverse distributional effects. The shadow price on root depth in this scenario is US$154 per cm. This is almost threefold that in the reference model.

The implications for the profitability of soil conservation investments are formidable, and very sensitive to our labour market assumptions. As the shadow price on labour approaches a more realistic level, the shadow price on root depth surges. In a context where land is crucial for employment provision, this may not be surprising. The value of the annual loss of root depth is about US$20 per ha. Compared to a return to wealth $W + I$, which is US$167 per ha, the value of lost root depth corresponds to about 12 per cent of the return on wealth. This is approximately the same as in the reference model.

Endogenous food prices As seen from Figure 1, production in the reference path will start below the current level and decline, and we might expect rising food prices. This effect is studied in the endogenous price version of the model. With endogenous crop prices, as described above, we find the wealth to be US$1,931 per ha, which is significantly higher than wealth with exogenous prices. The reason for this is mainly that the price of maize now is higher than in the reference scenario. The maize price starts at US$133 pre ton and rises to US$167 per ton over 50 years, while the benchmark price of maize is US$120 per ton.

Furthermore, the shadow price on root depth is now US$123 per cm, compared to US$54 per cm with exogenous prices. The value of annual soil losses then amounts to US$20 per ha, which is about 17 per cent of the return to wealth $W + I$.

Sensitivity analyses

Calibrating the model to the observed input mix would give $\alpha_L = 0.65$ whereas we have chosen the level $\alpha_L = 0.3$. Given the other elasticities, the production function exhibits constant returns to scale when $\alpha_L = 0.55$, and with constant returns to scale there is no resource rent. To assess the importance of the elasticities, we have made a simulation with $\alpha_L = 0.4$ too, which leaves some rent, but far less. In the reference model, the wealth per ha declines from US$1,156 to US$807 as the elasticity is increased, and the shadow price on root depth falls from US$54 per cm to US$30 per cm. Note, however, that with exogenous labour demand, $L_t = L_0$, and α_L does not enter the model, except for the calculation of shadow wages. The wealth $W + I$ is thus independent of α_L.

These results should be expected. As the reference scenario increases wealth compared to the benchmark by reducing labour input, we would expect less potential gains with a higher output elasticity on labour. Besides, the higher returns to scale are, the lower is the resource rent.

The choice of 4 per cent interest rate may be too low. Even an interest rate of 8 per cent may be moderate compared to interest rates facing poor farmers. As pointed out in the text, the optimal stock of nutrients is highly sensitive to changes in the interest rate. Consider the model with exogenous labour, where the optimal initial stock of nutrients is $N_0 = 3.3$ tons per ha, compared to about 2 tons per ha now. With $r = 8$ per cent the optimal initial stock drops to 1.1 tons per ha. The shadow price on root depth declines from US$154 per ha to US$55 per ha.

Despite of the sensitivity of N and shadowprices to changes in the interest rate, the effect on wealth is very modest. With exogenous labour, $W + I$ declines from US$2,501 to US$2,467, while in the reference model W declines from 1,156 to 1,141. The intuition is that as the interest rate decreases, farmers invest less in nutrients, and this reduction in initial investment about cancels out the effect of discounting future benefits.

As reported above, estimates of annual erosion rates range from 0.6 to 5.2 mm per ha. We have chosen a conservative estimate of 1.5 mm per ha. To evaluate the importance of this estimate we also present a sensitivity analysis of some of the key results in Table 6 below. Not surprisingly, the wealth is very sensitive to erosion rates. The estimated shadow price is also very sensitive to changes in the erosion rate. For low erosion rates, the sensitivity is less, especially for the exogenous labour version of the model, where the shadow price increases with increasing erosion rate, for low rates. With very low erosion rates, the root depth will not decline much within the time horizon relevant with 5 per cent interest rate. As the marginal productivity of root depth increases as depth decreases, the shadow price may actually increase with erosion rate, for low rates.

Hicksian income

Hicks' definition of income, adapted to national income, is the amount a nation can spend during a year and remain as well off at the end of the

Table 6. *Sensitivity towards erosion rate*

	Wealth					*P*				
Erosion rate: mm/ha	0.0	0.1	0.2	0.3	0.5	0.001	0.1	0.2	0.3	0.5
Reference model: *W*	1885	1347	953	728	508	65	59	47	37	25
Exogenous labour: *W* + *I*	5274	4650	3925	3093	1776	152	161	168	129	66

Note: Wealth *W* (including and present value of labour income *I* in US$ per ha for the exogenous labour scenario), for different assumptions about erosion rates. *P* is shadow price on rooting depth in US$ per cm x ha.

year as it was at the beginning. With constant interest rates and prices, the Hicksian income is equivalent to the return earned on national wealth. Since land rent is decreasing over time in some of our simulations and considerable initial investments are required in other, the observed income can deviate significantly from Hicksian income.

When labour supply is exogenous, the permanent income of the soil wealth including future labour income is about US$167 per ha. Due to heavy initial investment the first year, the cash flow is US$758 per ha, including labour income. To spend permanent income, it is necessary to borrow US$926 per ha. The second year cash flow including labour income is US$273 per ha, of which US$236 per ha remains after payment of interest. As productivity declines over time because the soil is eroding, US$68 per ha should be saved to maintain income over time. This is equivalent to a savings ratio of about 28 per cent.

With the current policy, the permanent income (excluding labour income) is US$44 per ha. In the first year the nutrient stock is adjusted downward. As the model is set up, the nutrient in soil is simply sold on the market, resulting in a financial wealth of US$336 per ha after consuming the Hicksian income. The second year, the cash flow including return to assets is US$76 per ha, and to consume only Hicksian income, US$32 per ha should be saved. Adding labour income, the contribution to GDP,[4] would be US$109 per ha, and thus the model prescribes a required savings ratio of about 29 per cent. Clearly, the nutrient stock in soil cannot be sold, and actually the adjustment of nutrient stock would take longer time. Adding this restriction to the model would reduce the wealth and hence the Hicksian income.

Thus in both cases, after an initial period of adjustments of stocks, the required savings ratio is about 28–9 per cent. The reason for this is that the soil is eroding, and unless part of the cash-flow is saved, the income will decline over time. Thus to maintain income over time, a significant share of the income should be saved. A similar calculation for the endogenous price case gives a required savings ratio of 13 per cent. While much lower, this is still high.

---

[4] Actually, the cash-flow is closer to NDP, since capital depreciation is subtracted. Capital depreciation is less than US$ pre ha.

6. Conclusions

The soil wealth estimates using the soil-mining model suggest that the gains from better utilisation of Tanzania's land resources may be considerable. The total soil wealth with the 1990/1 policies was estimated to US$2.9 billion. The optimal wealth was calculated to be US$13.1 billion. The magnitude of this finding is sensitive to the elasticities in the production functions, to the production functions themselves and to the data we have used. The figures should thus be interpreted with caution.

In section 5, the two-dimensional description of soil-quality was adopted and applied to study maize production in the Southern Highlands of Tanzania. We further extended the model with a version with fixed labour input and one with endogenous crop price. As the loss of rooting depth is irreversible, the production will decline over time. We estimate the value of the loss of rooting depth to 12–17 per cent of Hicksian income. Moreover, current profit is above income, as production is declining. To maintain consumption a savings rate in the range 13–19 per cent is required.

References

Alfsen, K, T. Bye, S. Glomsrød, and H. Wiig (1995), 'Integrated assessment of soil degradation and economic growth in Ghana', Document 95/8, Research Department, Statistics Norway.

Aune, J.B. (1995), 'Predicting soil degradation in Tanzania—a system analysis approach', in J.B. Aune and P.L. Sankhayan, eds., 'Structural adjustment policies and the management of soil- and forest resources in Tanzania', *Norwegian Journal of Agricultural Sciences*. Supplement no. **21**: 47–60.

Aune J.B. and R. Lal (1995), 'The tropical soil productivity calculator—a model for assessing the effects of soil management on productivity', in R. Lal and B.A. Stewart, eds., *Soil Management*: *Experimental basis for sustainability and environmental quality*. *Advances in Soil Science*, Boca Raton: CRC Press, Lewis Publishers, pp. 499–520.

Barber, R. (1986), 'An assessment of the dominant soil degradation processes in the Ethiopian highlands: their impacts and consequences', EHRS Working Paper 23, FAO/MoA.

Bates, R.H. (1981), *Markets and States in Tropical Africa: The Political Basis of Agricultural Policies*, Berkeley: University of California Press.

Bojø, J. (1996), 'The costs of land degradation in Sub-Saharan Africa', *Ecological Economics* **16**: 161–173.

Burt, O.R. (1981), 'Farm level economics of soil conservation in the Palouse Area of the Northwest', *American Journal of Agricultural Economics*, February: 83–92.

Crop Monitoring and Early Warning Unit (1993), 'Food Security Bulletin', July, Ministry of Agriculture, Dar es Salaam.

Elwell, H. and M.A. Stocking (1976), 'Vegetal cover to estimate soil erosion hazard in Rhodesia', *Geoderma* **15**: 61–70.

Elwell, H. and M.A. Stocking (1982), 'Developing a simple yet practical method of soil-loss estimation', *Tropical Agriculture* **59**(1): 43–48.

FAO (1993), *Quarterly Bulletin of Statistics*

FAO (1994), *Annual Yearbook of Production*, Rome.

Franco, M.A., S. Glomsrød, H. Høie, T. Johnsen, and E.M. Castillo (1993), 'Soil erosion and economic growth in Nicaragua', unpublished document, Statistics Norway.

Grepperud, S. (1995), 'Land degradation in developing countries', Ph.D. thesis, Department of Economics, University of Oslo.

Holden, S.T., B. Shiferaw, and M. Wik (1998), 'Poverty, market imperfections and time preferences: of relevance for environmental policy?', *Environment and Development Economics* **3**, 105–130.

Kamasho, J.A. (1995), 'Agroforestry in the Southern Highlands of Tanzania', in J.B. Aune and P.L. Sankhayan, eds., 'Structural adjustment policies and the management of soil- and forest resources in Tanzania', *Norwegian Journal of Agricultural Sciences*, Supplement No. 21: 47–60.

Marketing Development Bureau (1992), 'Summary review of agricultural marketing', Ministry of Agriculture, Dar es Salaam.

Marketing Development Bureau (1992), 'Annual review of cotton', Ministry of Agriculture, Dar es Salaam.

Marketing Development Bureau (1992), 'Annual review of maize, rice and wheat', Ministry of Agriculture, Dar es Salaam.

Marketing Development Bureau (1993), 'Annual review of coffee 1992/93', Ministry of Agriculture, Dar es Salaam.

Marketing Development Bureau (1993), 'Annual review of tobacco 1992/93', Ministry of Agriculture, Dar es Salaam.

Mascarenhas, A. (1991), 'An Overview of Deforestation Processes in Tanzania', Institute of Resource Assessment, University of Dar es Salaam.

Ministry of Agriculture, Tanzania (1992), 'Basic data, Agriculture and Livestock Sector 1984/85–1988/89'.

Parton, J.M., D.S. Schimel, C.V. Cole and D.S. Ojima (1987), 'Analyses of factors controlling soil organic matter dynamics in the Great Plains grassland', *Soil Science Society of America Journal* **51**: 1173–1179.

Pierce, F.J., W.E. Larson, R.H. Dowdy and W.A.P. Graham (1983), 'Productivity of soils: Assessing long-term changes due to soil erosion', *Journal of Soil and Water Conservation*, January–February: 39–44.

Roose, E.J. (1977), 'Adaptation des méthodes de conservation des sols aux condition écologiques et socio-économiques de l'Afrique de l'ouest', *L'Agronomie Tropical* **32**: 132–140.

Sankhayan, P.L. (1994), 'Effects of economic policy reforms on peasant agriculture and management of natural resources in Tanzania', Economy and development Paper No. 15, NLH, Ås. ISSN 0804–2144.

Sankhayan, P.L. (1995), 'Fertiliser marketing, distribution and use under structural adjustment programmes in Tanzania', Ecology and Development Paper No. 16, Agricultural University of Norway.

Stoorvogel, J.J. and E.M.A. Smaling (1990), 'Assessment of soil nutrient depletion in sub-Saharan Africa: 1983–2000', Report 28, The Winard Staring Center, Wageningen, Holland.

Sutcliffe, J.P. (1993), 'Economic assessment of land degradation in the Ethiopian highlands—a case study', National Conservation Strategy Secretariat, Ministry of Planning and Economic Development, Addis Ababa.

Taylor, D.B. and D.L. Young (1985), 'The influence of technological progress on the long run farm level economics of soil conservation', *Western Journal of Agricultural Economics* **10**(1): 63–76.

United Nations (1996), 'Statistical Yearbook', 41st Issue.

van den Brienk, R. (1992), 'A review of agricultural statistics of mainland Tanzania', Report, World Bank, Southern Africa Department, Agriculture Operations Division.

Weisensel, W.P. and G.C. Van Kooten (1990): 'Estimation of soil erosion time paths: the value of soil moisture and topsoil depth information', *Western Journal of Agricultural Economics* **15**(1): 63–72.

World Bank and Government of Tanzania (1992), 'Agriculture Sector Review'.

World Bank (1996), Towards environmentally sustainable development in Sub-Sahara Africa. A World Bank Agenda. Series: Development in Practice, The World Bank, Washington, 140 p.

Appendix 1

In the first model we consider the wealth maximisation problem

$$max \int_0^\infty (P_tQ_t - w_FF_t - w_LL_t - w_KI_t)e^{-rt}\,dt, \qquad (A.1.1)$$

subject to (1) to (4). The Hamiltonian of this system is

$$H = P_tQ_t - w_FF_t - w_KI_t - w_LL_t - \mu_t(I_t - \delta K_t) + \upsilon_t(F_t - nQ_t - \beta E_t), \qquad (A.1.2)$$

and to simplify these expressions, we introduce the net price on the product. Let

$$\gamma = -\frac{oE(Q)}{\partial Q} = b\phi\exp(-bQ),$$

be the marginal effect on erosion from a marginal increase in crop yield. Since the crop sells at market prices P, and will remove $n - \gamma$ units of nutrients from the soil, at a shadow value υ, the net price will be $p = P - \upsilon(n - \beta\gamma)$. The first-order conditions for optimal inputs of investments, labour and nutrients can now be written as

$$\begin{aligned} f_Lp &= w_L \\ \mu_t &= w_K \\ \upsilon_t &= w_F \end{aligned} \qquad (A.1.3)$$

and the dynamics of the adjoint variables

$$\begin{aligned} \dot{\mu}_t &= (r + \delta)\mu_t - f_Kp \\ \dot{\mu}_t &= r\upsilon_t - f_Np \end{aligned} \qquad (A.1.4)$$

Combining the first-order condition for investment with the differential equation for μ, we note that

$$pf_K = w_K(r + \delta - \frac{\dot{w}_K}{w_K}) \qquad (A.1.5)$$

which claims that investments should be chosen so that the marginal productivity of capital equals the user cost of capital. Similarly for investment in nutrient stocks

$$pf_N = w_F(r - \frac{\dot{w}_F}{w_F}), \qquad (A.1.6)$$

and in optimum the marginal productivity of soil quality should equal the 'user cost of soil capital'. To derive a closed form solution we use a Cobb–Douglas production function,

$$Q_t = A_tK_t^{\alpha_1}L_t^{\alpha_2}N_t^{\alpha_3} \qquad (A.1.7)$$

A_t is a scaling parameter incorporating technological progress. Since the production is restricted to a limited area of land, we assume decreasing returns to scale, i.e. $\alpha = \alpha_K + \alpha_L + \alpha_N < 1$. Assuming constant prices the optimality conditions (A.1.4) can be rewritten as

$$\begin{aligned} \alpha_K pQ &= (r+\delta)w_K K \\ \alpha_L pQ &= w_L L \\ \alpha_N pQ &= rw_F N \end{aligned} \tag{A.1.8}$$

as claimed in the text.

Appendix 2

In the model with root depth added as a stock, net-profit is unchanged, as there is no additional input factor. The problem is then to maximise (A.1.1) subject to (2) to (4) and (14) to (15). The Hamiltonian of the system now becomes

$$H_t = \pi_t + \mu_t(I_t - \delta K_t) + \gamma_t(F_t - nQ_t - \beta E_t) - \lambda_t E \tag{A.2.1}$$

The net price of the crop now equals $p = P - n\nu_t + \gamma(\nu_t + \lambda_t)$. The first order condition with constant input prices are

$$\begin{aligned} f_L p &= w_L \\ \mu_t &= w_K \\ \upsilon_t &= w_F \end{aligned} \tag{A.2.2}$$

The dynamics of the adjoint variables can be written as

$$\begin{aligned} \dot{\mu}_t &= r\mu_t - (f_K p - \delta) \\ \dot{\gamma}_t &= r\upsilon_t - f_N p \\ \dot{\lambda}_t &= r\lambda_t - f_D p \end{aligned} \tag{A.2.3}$$

Note that μ and ν are determined by the first-order conditions. It remains to determine λ to identify the optimal management regime.

Combining the first-order conditions and the dynamic equations for μ and υ, and using the Cobb–Douglas specification, the optimality conditions can be rewritten as

$$\begin{aligned} \alpha_1 pQ &= (r+\delta)w_K K \\ \alpha_2 pQ &= w_L L \\ \alpha_3 pQ &= rw_F N \end{aligned} \tag{A.2.4}$$

Note that this equation involves the shadow price of root depth λ since the net price p on output depends on the shadow value of soil erosion that is avoided when crop yields increase marginally. Once the initial level of λ is established, it is straightforward to compute the optimal policy and the path for λ. Hence, a procedure for wealth computation is to guess the value of λ, and simulate the optimal development given this value, and interate on the initial value of λ until $\lambda_T = 0$.