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# DETERMINANTS OF SUSTAINABILITY OF A COLOMBIAN HILLSIDE FARM

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## SUMMARY

This study applies systems simulation to characterize determinants of sustainability of a hillside farm in the upper Cauca River watershed of Colombia. A farm model linked to process-level crop models was used to simulate a set of farm scenarios. Sustainability, expressed as the probability of farm continuation, was estimated for each scenario based on replicated simulation with stochastic weather and price inputs. Hypotheses about determinants of sustainability were tested by sensitivity analysis. Results identify cropping system, area under cultivation, consumption requirements and crop prices as important determinants of sustainability. The study highlights the impacts of price variability and spatial diversification on farm risk and the results suggest ways to enhance the sustainability of the farm. The methodology was useful for integrating the diverse biophysical and economic factors that affect farm sustainability.

## INTRODUCTION

A growing interest in agricultural sustainability stems from concern about both threats to agriculture and negative impacts of agriculture, and from the realization that decisions made now can have unforeseeable impacts in the future. Little progress has been made towards developing methods for characterizing sustainability of agricultural systems because of the conceptual problem of agreeing on a definition and the practical problems that result from the fact that sustainability deals with the future and cannot be readily observed or measured using traditional experimental methods. Methods proposed based on the current state or past behaviour of a system suffer logical and practical deficiencies (Hansen, 1996b). If sustainability is based on adherence to prescribed practices such as reduced chemical use (Dobbs *et al.*, 1991; Cordray *et al.*, 1993), then the role of those practices as determinants of sustainability cannot be evaluated objectively. Likewise, indices of sustainability that consider many system attributes (Jodha, 1990; Torquebiau, 1992; Stockle *et al.*, 1994) do not provide a basis for ranking the importance of those attributes as determinants of sustainability. Trends of past system outputs or inputs (Lynam and Herdt, 1989; Monteith, 1990) are difficult to extrapolate, and do not deal correctly with

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the role of variability about the trend. Likewise, system resilience ignores several factors that affect sustainability.

This study applies a framework proposed by Hansen and Jones (1996) for using stochastic simulation of a farm to characterize sustainability defined as the probability of violating specified failure thresholds within a particular interval. Other farm simulation studies (reviewed by Klein and Narayanan, 1992, and Jones *et al.*, 1996) have examined factors that contribute to the probability of farm failure. For example, the FLIPSIM farm financial model (Richardson and Nixon, 1985) has been used to study the impacts of farm size (Richardson and Condra, 1981), price variability (Grant *et al.*, 1984), marketing strategies (von Bailey and Richardson, 1985), tenure arrangements and several other policy and management factors on farm survivability. The current study is unique in that it combines biophysical models with a whole-farm simulation model to examine a broad range of physical, biological and economic determinants of sustainability.

The Cauca River watershed in the lower Andes of southwestern Colombia is undergoing a transition that challenges its smallholder farmers (Ashby, 1985). For 25 years, coffee (*Coffea arabica*) provided an adequate but variable level of income to farmers, while providing continuous canopy and ground cover to protect the steep soils from erosion. Declining world coffee prices and the spread of a new seed-boring insect pest, broca (*Hypothenemus hampei*), have reduced the ability of coffee to provide for farmers' livelihood. In the early 1990s, the Colombian Coffee Federation offered one-time monetary incentives for farmers in marginal areas to abandon coffee production to slow the spread of broca and to boost declining market prices. Farmers who participated found themselves with some financial capital but few good alternative enterprises and a highly uncertain future. Ashby (1985) argued that the shift from perennial coffee to annual crops reflects a shift in farmers' priorities from long-term environmental conservation to short-term economic returns. The annual crops that are replacing coffee leave steep soils exposed to erosive rains. Resulting soil erosion may irreversibly reduce crop production and cause off-farm effects such as siltation, chemical pollution, and regulation of flow rates in the strategic Cauca River.

In this study, we applied a systems framework for characterizing sustainability to a Colombian hillside farm to demonstrate the approach, and to gain insight into the impact of cropping system, soil nitrogen management, costs and prices, resource endowment and sources of risk on sustainability of that farm. These insights suggested ways that the farmer, researchers and policymakers might improve farm sustainability expressed as long-term economic viability.

## MATERIALS AND METHODS

### *Characterizing farm sustainability*

The approach used in this study (Hansen and Jones, 1996) was based on the following definition of sustainability: 'the probability that a particular system will not meet specified criteria for failure during a particular future period.' If we let $t_F$

be time to failure, a random variable with a cumulative distribution, $\mathrm{F}_{t\mathrm{F}} = \mathbf{P}\{t_\mathrm{F} \leq t\}$, then we can define sustainability for the period $(0, t]$ as,

$$S(t) = 1 - \mathrm{F}_{t\mathrm{F}} \tag{1}$$

With appropriate definitions of failure, the definition in Equation 1 is equivalent to the survival function in mortality studies and to reliability in quality control literature (Elandt-Johnson and Johnson, 1980; Kalbfleisch and Prentice, 1980). When failure is expressed in terms of farmer livelihood goals (as in this study), this becomes primarily an economic definition. Yet it integrates the effects of environmental and social factors that influence farm production and household consumption. Failure criteria could also be expressed in environmental terms as, for example, violation of threshold levels of pollution, although such thresholds would more often be treated as production system constraints.

Although sustainability as we define it cannot be measured directly, it can be estimated from long-term, stochastic simulation of a model of the system. In this study, we simulated 100 replicates of each of several 15-year scenarios, with stochastic weather and price inputs. Let $N$ be the number of stochastic realizations of a farm scenario simulated, and $n(t)$ the number continuing at time $t$. Sustainability through time $t$ can then be estimated from simulation results as

$$\hat{S}(t) = n(t)/N, \tag{2}$$

with a standard error of

$$\mathrm{s.e.}_{\hat{S}} = \sqrt{n(t)(N - n(t))/N^3}. \tag{3}$$

Hypotheses about determinants of sustainability are tested by sensitivity analysis of simulation results of a base scenario that represents the best assumptions about the farming system and its environment. The impacts of continuously varying parameters, such as land area, mean prices or fertilizer rates, on predicted sustainability can be ranked by relative sensitivity,

$$\lambda_i = \frac{Y_{i,0}}{|Y_i - Y_{i,0}|} \cdot \frac{\hat{S}_i - \hat{S}_0}{\hat{S}_0}, \tag{4}$$

where $Y_{i,0}$ is the value of parameter $i$ in the base scenario, $Y_i$ is its adjusted value, and $\hat{S}_0$ and $\hat{S}_i$ are sustainability values estimated for the base and alternative scenarios respectively. The impacts of discrete factors, such as cropping system, are ranked by absolute sensitivity:

$$\Lambda_i = \hat{S}_i - \hat{S}_0. \tag{5}$$

Estimated sustainabilities of alternative scenarios are compared based on the McNemar test statistic ($G_{\mathrm{P,adj}}$) (McNemar, 1947; Sokal and Rohlf, 1981). Sustainabilities of two scenarios are considered different if $G_{\mathrm{P,adj}} > \chi^2_{0.05,1}$. The McNemar test statistic can be undefined if, for example, none of the replicates that continue in a base scenario fail in an alternate scenario. When this happens, simulated sustainabilities are compared based on the log-likelihood ratio test statistic ($G_{\mathrm{I,adj}}$) for independent observations, which is conservative when applied to paired observations (Sokal and Rohlf, 1981).

### *A Colombian hillside farm*

A farm in the Cabuyal River catchment (lat 2°47′N, long 76°31′W) was selected for the simulation study. Farm selection was based on several criteria. The size of the farm (5.2 ha, of which 2.3 ha were cultivated with annual crops), its elevation (1650 m), topography and soils, and the size of the farm household (six members) typified farms in the Cabuyal area. However, the farmer considered in this study was regarded as an innovator with a high level of technical knowledge. He has cooperated with researchers from CIAT (International Center for Tropical Agriculture) by providing information, recording weather data, and providing land for on-farm maize, bean and cassava trials. The description of the farm household, resources and management of crop enterprises was taken from a formal survey conducted by CIAT in September 1993, and from subsequent interviews with the farmer.

The farm supported six family members: the farmer, his mother, wife and three children. One daughter was attending a state university, and another planned to attend soon. They lived in a five-room stucco house of above-average quality for the area. Access to the farm was by a well-maintained gravel road 2 km from a small town and 4 km from a major highway.

Coffee was the only commercial enterprise until July 1993, when the farmer accepted a monetary incentive to remove his coffee crop. He has since used the land (2.38 ha) that had been in coffee production for maize sold as green ear (*choclo*) for the fresh market and beans for market and household consumption.

### *Topography and soils*

The farm landscape was quite steep; about one-third of the area had slopes greater than 24%. The soil was a medial, isothermic, acrudoxic Hydric Hapludand (Castro *et al.*, 1992). Soils were sampled at eight locations on the farm in January 1994 and analysed for physical and chemical properties. A moisture release curve was used to find saturated ($SAT$) water content (0 atm) and lower limit ($LL$) of plant-extractable water ($-15$ atm). Drained upper limit ($DUL$) of plant-extractable water was measured in the field. The soils were deep ($>2$ m), well-drained, generally phosphorus-deficient, high in organic carbon (4–12% in the Ap horizon) and total nitrogen (0.55–0.78% in the Ap horizon), and with low bulk densities (0.41–0.45 g cm$^{-3}$) and high plant-available water-holding capacities (0.14–0.16 cm$^3$ cm$^{-3}$). Hansen (1996a) presented measured and derived soil parameters. For the simulation study, the farm was divided into six fields using four of the sampled soils.

### *Weather*

Rainfall, minimum and maximum temperature, and solar radiation were measured on the study farm for 19 months before the simulation study. Because long-term weather records were not available near the study farm, monthly climate parameters (Table 1) were estimated from records of six surrounding stations (lat 2.42 to 3.08°N, long 76.46 to 76.58°W, 990 to 1850 m asl) using inverse-squared-distance interpolation, with temperatures adjusted for an adiabatic lapse rate of 6 °C per 1000 m increase in elevation (Hansen, 1996a).

### *Resources*

The farmer routinely hired day-labourers on a contract basis for field operations because there was a shortage of family labour. Production inputs such as seed, fertilizers and pesticides were readily available. The farmer did not own any farm equipment other than simple hand tools; credit from institutional sources was difficult to obtain and terms were unfavourable.

We assumed that the farmer had Col$ 4 000 000 (Col$ 1 700 000 savings + 2 300 000 payment for removing coffee) of savings in September 1994. He estimated his minimum annual household expenses at Col$ 3 000 000. We adjusted this amount down to Col$ 2 250 000 on the assumption that the family could endure more scarcity than he estimated. Discretionary spending was assumed to be 20% of liquid assets (that is, monetary savings plus the value of any stored harvest products) per year. The family's annual household expenses were high for the region because of college expenses for the eldest daughter. Besides monetary expenditures, the household was assumed to consume 650 kg maize and 150 kg beans annually.

### *Crop enterprises*

Information about crop management came from interviews with the farmer and a neighbouring tomato farmer, unpublished enterprise budgets and discussions with CIAT personnel familiar with the region. Table 2 summarizes crop management assumptions. A recovery factor for each crop (Table 3) accounts for harvest losses and yield-reducing factors that the crop models do not consider, such as phosphorus deficiency, pests and diseases. The low recovery factor for tomato was based on the difference between simulated yields and those reported by a farmer in Siberia, about 2 km from the study farm. It reflected the vulnerability of tomato to loss from diseases and the impossibility of marketing deformed or damaged fruit. The recovery factor for cassava (0.4) reflected the fact that the cassava model (CropSim CASSAVA v. 1.0, Hoogenboom *et al.*, 1994) does not account for the nitrogen stress expected under typical management. The recovery factors for bean and fresh maize assumed good control of weeds and pests.

Table 1. *Spatially interpolated monthly WGEN coefficients for the study farm, Cauca, Colombia*

| | Radiation (MJ $m^{-2}$ $d^{-1}$) | | | | Temperature (°C) | | | | | | Rainfall | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Maximum | | | | Minimum | | | | | |
| | Dry days | | Wet days | | Dry days | | Wet days | | All days | | | | | |
| Month | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | α† | Total (mm) | P{DW}‡ | Number of wet days |
| Jan. | 18.5 | 4.0 | 15.5 | 4.1 | 26.1 | 1.7 | 24.7 | 1.9 | 14.5 | 1.2 | 0.875 | 178.5 | 0.293 | 13.2 |
| Feb. | 19.1 | 4.0 | 15.5 | 4.2 | 26.2 | 1.8 | 24.7 | 1.9 | 14.7 | 1.2 | 0.888 | 181.5 | 0.294 | 13.1 |
| Mar. | 18.7 | 4.6 | 15.2 | 4.7 | 26.1 | 1.6 | 25.0 | 2.1 | 14.8 | 1.2 | 0.780 | 220.3 | 0.337 | 15.1 |
| Apr. | 17.7 | 4.5 | 14.3 | 4.0 | 25.8 | 1.5 | 24.8 | 1.8 | 14.9 | 1.0 | 0.898 | 221.5 | 0.416 | 16.1 |
| May | 17.0 | 4.4 | 14.0 | 3.8 | 25.8 | 1.5 | 24.5 | 1.8 | 14.9 | 1.1 | 0.740 | 183.1 | 0.363 | 16.0 |
| Jun. | 17.8 | 3.6 | 14.3 | 3.5 | 26.0 | 1.5 | 24.4 | 1.7 | 14.4 | 1.1 | 0.803 | 93.3 | 0.238 | 11.2 |
| Jul. | 18.1 | 3.7 | 15.1 | 3.1 | 26.2 | 1.6 | 24.9 | 1.6 | 13.8 | 1.4 | 0.857 | 68.8 | 0.161 | 7.8 |
| Aug. | 18.3 | 4.0 | 15.1 | 3.8 | 27.0 | 1.7 | 24.9 | 1.9 | 13.9 | 1.3 | 0.743 | 79.8 | 0.157 | 7.6 |
| Sep. | 18.1 | 4.2 | 16.2 | 4.1 | 26.5 | 1.9 | 25.1 | 1.9 | 14.2 | 1.1 | 0.935 | 119.2 | 0.259 | 11.1 |
| Oct. | 16.9 | 4.4 | 14.9 | 4.1 | 25.4 | 1.7 | 24.7 | 1.8 | 14.5 | 1.2 | 0.865 | 245.9 | 0.454 | 18.0 |
| Nov. | 17.1 | 4.1 | 14.4 | 3.9 | 25.4 | 1.5 | 24.5 | 1.8 | 14.8 | 1.3 | 0.872 | 274.5 | 0.449 | 17.9 |
| Dec. | 17.6 | 3.9 | 14.8 | 3.8 | 25.6 | 1.4 | 24.7 | 1.7 | 14.7 | 1.2 | 0.951 | 189.7 | 0.342 | 14.2 |

†alpha parameter of the gamma distribution; ‡probability that a day is wet and was preceded by a dry day; $s$ = standard deviation.

Table 2. *Management assumptions used for crop simulation*

| Crop | Cultivar | Planting | | | | Critical moisture† | Row width | Nitrogen applied (kg ha$^{-1}$) on day | |
|---|---|---|---|---|---|---|---|---|---|
| | | Method | Density (m$^{-2}$) | Depth (cm) | Earliest date | (ml g$^{-1}$) | (cm) | 1‡ | 28‡ |
| Maize | CIMCALI | seed | 5.00 | 4 | 17 Sep. | 0.35 | 60 | 25 | 25 |
| Early bean | ICA Caucaya | seed | 16.60 | 2 | 17 Sep. | 0.40 | 30 | 25 | 0 |
| Late bean | ICA Caucaya | seed | 16.60 | 2 | 6 Mar. | 0.40 | 30 | 25 | 0 |
| Cassava | MCol-1501 | cutting | 0.70 | 10 | 10 Jan. | 0.30 | 100 | 0 | 0 |
| Tomato | Sunny | transplant | 0.75 | 10 | 21 Mar. | 0.35 | 150 | 75 | 75 |

†threshold soil water content relative to $DUL - LL$ (drained upper limit minus lower limit of plant extractable water), averaged to 30 cm depth, below which automatic irrigation occurs; ‡days after planting.

Table 3. *Adjustments to simulated yields and reported prices, Cauca, Colombia*

| Product | Recovery† | Moisture adjustment‡ | Quality adjustment§ | Market discount¶ |
|---|---|---|---|---|
| Coffee | 1.00 | 1.00 | 0.90 | 1.00 |
| Cassava | 0.40 | 2.86 | 1.00 | 0.20 |
| Fresh maize (*choclo*) | 0.80 | 1.90 | 1.00 | 0.70 |
| Tomato (Manalucie) | 0.40 | 16.67 | 1.00 | 0.70 |
| Bean (Radical) | 0.80 | 1.00 | 1.00 | 0.65 |

†ratio of expected harvest to potential yield, dry basis; ‡ratio of market to dry weight; §discount due to difference in quality or cultivar; ¶ratio of price paid to farmer to price paid by wholesaler.

Table 4 gives labour requirements for each operation. We assumed (a) that the farmer hired day-labourers for field preparation, planting, weeding, tying tomato plants, pruning coffee, harvesting and post-harvest processing, (b) that he irrigated, sprayed pesticides, applied fertilizer as a side-dressing, prepared tomato seedlings and pruned tomatoes himself if he had time, otherwise he hired day-labourers, and (c) that he took care of marketing himself.

*Prices*

Historical price data were from wholesaler records for cassava, maize and tomato (Corporation de Abastecimentos del Valle del Cauca, 1994, unpublished report), from a study of retail prices of beans (W. C. Castillo, CIAT, 1990, 1994, unpublished reports), and from published sources for chemical inputs (Anonymous, 1994), coffee and consumer price indices (CPI) (Banco de la Republica, various dates). We deflated prices to a constant December 1992 basis using monthly CPI for Cali. Prices are presented in Fig. 1 for crops and in Table 5 for purchased inputs and labour.

Stochastic price realizations were generated as the sum of a deterministic, seasonally-adjusted trend (Equation 6) and a stochastic, multivariate time-series process (Equation 7). Log-transformed crop prices were fitted to a seasonally adjusted trend,

$$x_t = \alpha + \beta t + \mu_m, \tag{6}$$

where $x_t$ is the expected value of the log-transformed price at $t$ months after a specified base month, $\alpha$ and $\beta$ are the slope and intercept of a linear trend, and $\mu_m$ is the mean deviation from the linear trend for calendar month $m$ (for example, $\mu_1$ is the mean deviation from the trend for all Januaries). The resulting residuals were then fitted to a multiplicative ARMA model (Box and Jenkins, 1970):

$$w_t = \sum_{i=1}^{p} \phi_i w_{t-i} + \sum_{i=1}^{q} (\theta_i(\theta_s \varepsilon_{t-i-qs} - \varepsilon_{t-i})) + \varepsilon_t - \theta_s \varepsilon_{t-qs}, \tag{7}$$

Table 4. *Estimated number of crop production operations per season (No.) and labour required (hours per hectare per operation unless otherwise indicated (Hours)), study farm, Cauca, Colombia*

| | Maize | | Bean | | Cassava | | Tomato | | Coffee | |
|---|---|---|---|---|---|---|---|---|---|---|
| Operation | No. | Hours | No. | Hours | No. | Hours | No. | Hours | No. | Hours |
| Seedbed preparation | — | — | — | — | — | — | 1 | 12 | — | — |
| Primary tillage | 1 | 24 | 1 | 24 | 1 | 24 | 1 | 24 | — | — |
| Planting | 1 | 40 | 1 | 96 | 1 | 80 | 1 | 39 | — | — |
| Fertilizer application: | | | | | | | | | | |
| pre-planting | 1 | 24 | 1 | 24 | — | — | 1 | 24 | — | — |
| side dressing | 1 | 8 | — | — | — | — | 1 | 8 | 2 | 8 |
| Weeding | 1 | 120 | 1 | 120 | 4 | 60 | 1 | 120 | — | — |
| Pesticide application | — | — | 4 | 8 | — | — | 10 | 8 | 4 | 8 |
| Staking | — | — | — | — | — | — | 1 | 72 | — | — |
| Pruning and tying | — | — | — | — | — | — | 4 | 15 | 3 | 150 |
| Harvest (h $t^{-1}$) | 1 | 20 | 1 | 60 | 1 | 30 | 1 | 40 | 8 | 40 |
| Processing (h $t^{-1}$) | — | — | 1 | 100 | — | — | — | — | 8 | 400 |
| Marketing (h $t^{-1}$) | 1 | 6 | 1 | 3 | 1 | 9 | 1 | 9 | 8 | 3 |
| Field cleaning | 1 | 60 | — | — | — | — | — | — | 3 | 60 |
| Total (h $t^{-1}$)† | | 560 | | 598 | | 515 | | 812 | | 1298 |

†based on representative harvest yields (4 t $ha^{-1}$ for maize, 2 t $ha^{-1}$ for bean, 9 t $ha^{-1}$ for cassava, 10 t $ha^{-1}$ for tomato and 2.25 t $ha^{-1}$ for coffee).

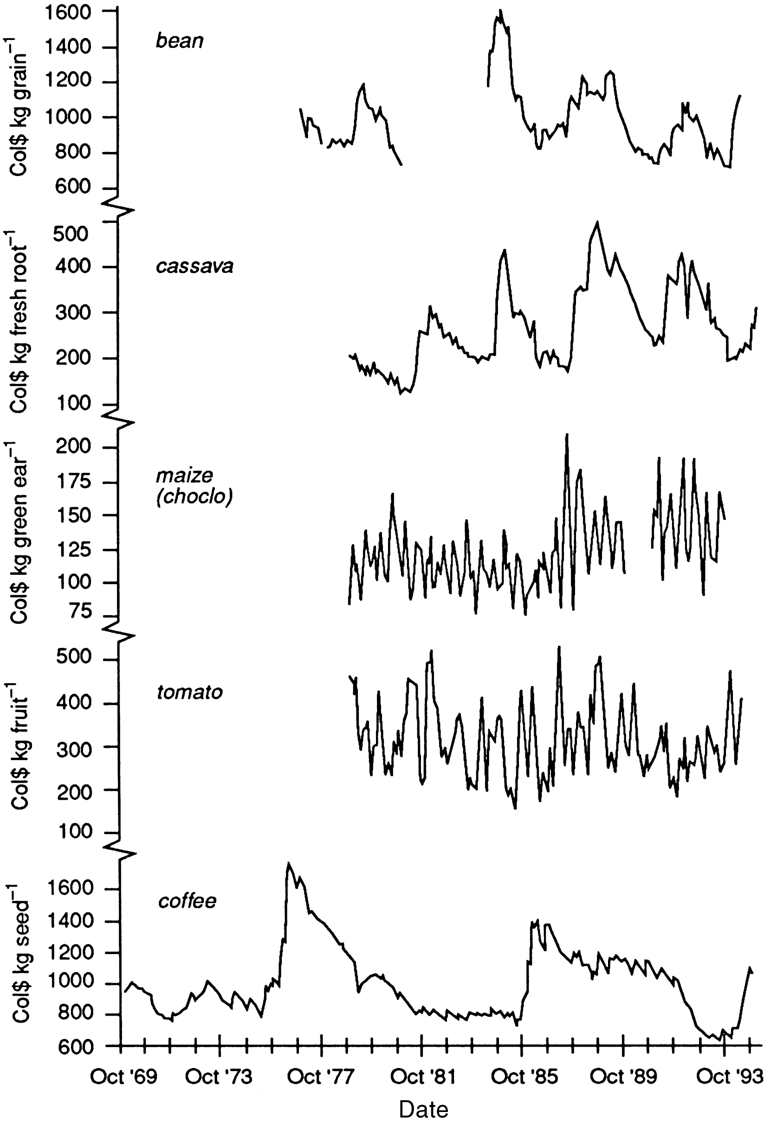

Fig. 1. Inflation-adjusted historical crop wholesale prices, Cauca, Colombia.

where $w_t$ is the deviation from the seasonally adjusted trend (Equation 6) in month $t$, $\phi_i$ and $\theta_i$ are autoregressive and moving average coefficients for a lag of $i$ months, $p$ and $q$ are the maximum lags of the autoregressive and moving average components, $qs$ is the lag of an optional multiplicative seasonal moving average component ($\theta_s$), and $\varepsilon_t$ is a random normal deviate. Values of $p$ and $q$ ($\leq 6$) were selected that minimized the corrected Akaike's information criterion statistic (Brockwell and Davis, 1991). Coffee was the only crop with a significant multiplicative seasonal moving-average component. The model accounted for cross-price correlation by sampling each $\varepsilon_t$ from a multivariate normal distribu-

Table 5. *Prices (Col$) of production inputs, Cauca, Colombia, December 1992*

| Input | Unit | Price |
|---|---|---|
| Day labour wage | h | 220.00 |
| Contracted ploughing | h | 1430.00 |
| Maize seed | kg | 900.00 |
| Bean seed | kg | 1600.00 |
| Tomato seed | g | 2600.00 |
| Cassava cuttings | kg | 50.00 |
| Chicken manure | kg N | 1422.00 |
| 10–30–10† | kg N | 1980.00 |
| 17–6–18–2‡ | kg N | 1006.50 |
| Manzate | kg | 3443.00 |
| Roxión | kg | 5324.00 |
| Benomyl | kg | 16 487.00 |
| Copper oxychloride | kg | 1902.00 |
| Poles | each | 13.00 |
| Irrigation water | mm $ha^{-1}$ | 100.00 |

†10%N, 30%$P_2O_5$, 10%$K_2O$;‡17%N, 6%$P_2O_5$, 18%$K_2O$, 2%Mg.

tion, $\boldsymbol{\varepsilon} \sim \mathbf{N}(0, \Sigma)$, where $\Sigma$ was the variance-covariance matrix calculated from the residuals of the individual fitted price series models (Hipel and McLeod, 1994). Tables 6 and 7 give the fitted parameters used to generate crop prices.

Multipliers used to convert from wholesale to farmgate prices accounted for differences between dry weight and reported moisture contents, for price differences due to quality or cultivar, and for differences between reported wholesale and farmgate prices (Table 3). Market discounts were based on a farmer interview (maize) and discussions with CIAT economists familiar with the region (coffee, cassava and bean).

### *Scenarios*

Simulation was used to test hypotheses about the role of cropping system, coffee yields, nitrogen fertilizer, prices, household consumption, resource endowment, labour source and credit as determinants of farm sustainability (Table 8). Each of a set of farm scenarios (Table 9) was simulated for the 15-year period beginning September 1994. For each scenario, the 15-year period was replicated 100 times with different stochastic realizations of weather and prices. A *base* scenario served as a basis for comparing the other scenarios and testing hypotheses. The cropping system in the *base* scenario was a three-year rotation of maize, beans and cassava (Fig. 2) and the three phases of the rotation were distributed among fields of equal area. Although the analyses included several cropping systems (Fig. 2), management of each crop was similar in all of the annual cropping systems.

We simulated four additional scenarios to examine the effects of weather variability, price volatility and spatial diversification on farm risk and sustainability (hypotheses 16 and 17, Table 8). The role of each of the two stochastic inputs (weather and prices) was examined by restricting the other input to a

Table 6. *Fitted parameters for deterministic component (Equation 4) of crop price time series models*

| | Trend | | Monthly mean deviation from trend | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crop | $\alpha$ | $\beta$ | $\mu_{\text{Jan.}}$ | $\mu_{\text{Feb.}}$ | $\mu_{\text{Mar.}}$ | $\mu_{\text{Apr.}}$ | $\mu_{\text{May}}$ | $\mu_{\text{Jun.}}$ | $\mu_{\text{Jul.}}$ | $\mu_{\text{Aug.}}$ | $\mu_{\text{Sep.}}$ | $\mu_{\text{Oct.}}$ | $\mu_{\text{Nov.}}$ | $\mu_{\text{Dec.}}$ |
| Coffee | 3.0035 | −0.0001 | 0.0005 | −0.0070 | −0.0031 | 0.0008 | −0.0019 | 0.0028 | −0.0030 | 0.0006 | 0.0002 | 0.0035 | 0.0034 | 0.0035 |
| Cassava | 2.2553 | 0.00073 | 0.0143 | 0.0056 | 0.0060 | 0.0134 | 0.0112 | 0.0373 | 0.0231 | 0.0091 | 0.0015 | 0.0055 | 0.0117 | 0.0247 |
| *Choclo* | 1.9643 | 0.00055 | 0.0754 | 0.0044 | 0.0501 | 0.0634 | 0.0189 | 0.0665 | 0.0461 | 0.0136 | 0.0796 | 0.0695 | 0.0081 | 0.0659 |
| Tomato | 2.5335 | −0.0003 | 0.0075 | 0.0395 | 0.0637 | 0.0711 | 0.0225 | 0.0296 | 0.0273 | 0.0364 | 0.0343 | 0.0118 | 0.0343 | 0.0244 |
| Bean | 3.0079 | −0.0001 | 0.0064 | 0.0106 | 0.0104 | 0.0021 | 0.0075 | 0.0127 | 0.0078 | 0.0021 | 0.0090 | 0.0016 | 0.0052 | −0.0003 |

Table 7. *Fitted parameters for stochastic component (Equation 5) of crop price time series models*

| | Shock | Autoregressive terms | | | | | | Moving average terms | | | | | Seasonal | | Cross-correlation coefficients | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crop | $\sigma_\varepsilon$ | $\phi_1$ | $\phi_2$ | $\phi_3$ | $\phi_4$ | $\phi_5$ | $\phi_6$ | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\theta_5$ | $qs$ | $\theta_s$ | $r_{\text{coffee}}$ | $r_{\text{cassava}}$ | $r_{choclo}$ | $r_{\text{tomato}}$ | $r_{\text{bean}}$ |
| Coffee | 0.01813 | 0.069 | 0.871 | 0.261 | 0.271 | 0.000 | 0.000 | 1.034 | 0.308 | 0.000 | 0.000 | 0.000 | 62 | 0.126 | 1.00 | | | | |
| Cassava | 0.03458 | 1.014 | 0.024 | 0.630 | 0.664 | 0.000 | 0.000 | 0.043 | 0.123 | 0.602 | 0.173 | 0.000 | 0 | 0.000 | 0.10 | 1.00 | | | |
| *Choclo* | 0.05115 | 0.387 | 0.445 | 0.000 | 0.000 | 0.000 | 0.000 | 0.959 | 0.048 | 0.017 | 0.086 | 0.167 | 0 | 0.000 | −0.06 | −0.13 | 1.00 | | |
| Tomato | 0.07315 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.955 | 0.555 | 0.246 | 0.000 | 0.000 | 0 | 0.000 | 0.13 | 0.04 | 0.00 | 1.00 | |
| Bean | 0.02098 | 0.916 | 0.110 | 0.109 | 0.016 | 0.005 | 0.229 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0 | 0.000 | 0.32 | −0.03 | 0.11 | 0.14 | 1.00 |

Table 8. *Hypotheses related to determinants of sustainability of the study farm*

| Determinant | Hypothesis |
|---|---|
| Cropping system | 1. Farm sustainability is dependent on cropping system |
| | 2. Diversified crop rotations contribute to a more sustainable farming system than do monocultures |
| | 3. Incorporating a highly valued, irrigated vegetable (that is, tomato) into a rotation of traditional crops enhances farm sustainability |
| | 4. Sustainability of a farm in coffee monoculture is positively related to coffee yield |
| Soil management | 5. Either excessive or insufficient nitrogen fertilizer reduces farm sustainability |
| Costs and prices | 6. Low prices for crop products constrain farm sustainability |
| | 7. High material input prices constrain farm sustainability |
| | 8. High wages for hired labour constrain farm sustainability |
| | 9. A high subsistence spending requirement constrains farm sustainability |
| | 10. A high level of discretionary spending constrains farm sustainability |
| Resources | 11. The decision not to cultivate the land now in grass fallow constrains farm sustainability |
| | 12. Limited initial savings constrains farm sustainability |
| | 13. Access to credit enhances farm sustainability |
| | 14. When credit is available, farm sustainability is negatively related to loan interest rate |
| | 15. When credit is available, increasing supply increases farm sustainability |
| Sources of risk | 16. Weather and price variability contribute unequally to farm risk and to the probability of failure |
| | 17. Spatial diversity reduces farm risk and enhances sustainability |

single, deterministic realization for all replicates. This eliminated risk in the form of variability between replicates, but did not remove the pattern of year-to-year variability. To eliminate price risk, we used historical prices from August 1979 to September 1988 adjusted for their historical trends (Hansen, 1996a) as a proxy for future prices. As there were gaps in the historical sequences, bean prices used were from September 1978 to June 1980 and July 1984 to September 1988, and maize prices were from August 1979 to September 1989. Weather risk was eliminated by identifying the replicate of the *base* scenario with the median value of liquid assets after nine years, then applying the random number seed used to generate weather for that replicate to each replicate of the *no weather risk* scenario. The *no spatial diversification* scenario was a modification of the *base* scenario in which all cultivated land was in the same rotation phase. We simulated these four scenarios for only three rotation cycles (nine years) because only 11 full years of prices were available for all five crops and because of the difficulty of interpreting risk when distributions were truncated by many failures.

### *Crop simulation*

The dynamic, process-level crop simulation models used in this study were part of the Decision Support System for Agrotechnology Transfer version 3 (Hoogenboom *et al*., 1994): CROPGRO v. 3.0 for bean (*Phaseolus vulgaris* L.) and tomato (*Lycopersicon esculentum* Mill.), Generic-CERES v. 3.1 for maize (*Zea mays* L.), and CropSim-CASSAVA v. 1.0 for cassava (*Manihot esculenta* L.). An adaptation of

Table 9. *Description of 15-year farm scenarios and hypotheses they are designed to test*

| Scenario | Description | Hypotheses† |
|---|---|---|
| Base scenario | A three-year maize–bean–bean–cassava rotation used as a basis for comparing other scenarios in sensitivity analysis | all |
| Maize–bean | A one-year double-crop | 1 |
| Maize–bean–cassava | A two-year rotation | 1 |
| Maize monoculture | A one-year maize–maize double-crop | 1, 2 |
| Cassava monoculture | A three-year double crop | 1, 2 |
| Maize–tomato–bean–cassava | A three-year rotation, with irrigation for tomato and bean | 1, 3 |
| Coffee @ 1.75 t ha$^{-1}$ | Coffee monoculture with an annual yield of 1.75 t ha$^{-1}$ | 1, 4 |
| Coffee @ 2.00 t ha$^{-1}$ | Coffee monoculture with an annual yield of 2.00 t ha$^{-1}$ | 1, 4 |
| Coffee @ 2.25 t ha$^{-1}$ | Coffee monoculture with an annual yield of 2.25 t ha$^{-1}$ | 1, 4 |
| Coffee @ 2.50 t ha$^{-1}$ | Coffee monoculture with an annual yield of 2.50 t ha$^{-1}$ | 1, 4 |
| Less nitrogen fertilizer | 10–30–10 applied at 50% of *base* scenario (25 kg N ha$^{-1}$ split application to maize and 12.5 kg N ha$^{-1}$ to bean)‡ | 5 |
| More nitrogen fertilizer | 10–30–10 applied at 200% of *base* scenario (100 kg N ha$^{-1}$ split application to maize and 50 kg N ha$^{-1}$ to bean) | 5 |
| Higher commodity prices | 10% higher production commodity prices | 6 |
| Lower input prices | 20% lower material input prices | 7 |
| Lower labour prices | 20% lower prices for labour and ploughing | 8 |
| Less subsistence spending | 10% lower subsistence requirements for money, maize and bean | 9 |
| Less discretionary spending | 20% lower discretionary spending | 10 |
| More cultivated land | Additional land (0.23 ha, or 10% of currently cultivated area) cropped | 11 |
| More initial funds | 20% higher initial operating fund | 12 |
| Credit @ 19% | Col$ 2 000 000 available at 19% interest, 24 month repayment schedule | 13 |
| Credit @ 9.5% | Col$ 2 000 000 available at 9.5% interest, 24 month repayment schedule | 14 |
| More credit | Col$ 3 000 000 available at 19% interest, 24 month repayment schedule | 15 |

†hypotheses are listed in Table 5; ‡10–30–10 = 10%N, 30%$P_2O_5$, 10%$K_2O$.

WGEN (Richardson, 1985) incorporated in the crop models provided stochastic weather inputs based on monthly climate parameters derived from historical weather from neighbouring locations.

The CERES maize model has been tested extensively in temperate North America and Europe (Kiniry and Jones, 1986) and in various regions in tropical Africa (Keating *et al.*, 1991; Singh *et al.*, 1993), Asia and the Pacific (Singh, 1985) with generally acceptable results. Simulated maize yields matched observed yields closely in a Hawaiian Andisol (Ritchie *et al.*, 1990b). Although CROPGRO is relatively new and its ability to predict growth and development of field bean has undergone only limited testing (Boote *et al.*, 1997), its predecessor, BEANGRO v.1.01, has been tested in Colombia (White *et al.*, 1995). Predictions of yield response to population density and water stress were generally good, but phenology predictions were poorer. CROPGRO has been adapted to simulate field-grown tomato (Scholberg *et al.*, 1996); validation work is in progress.

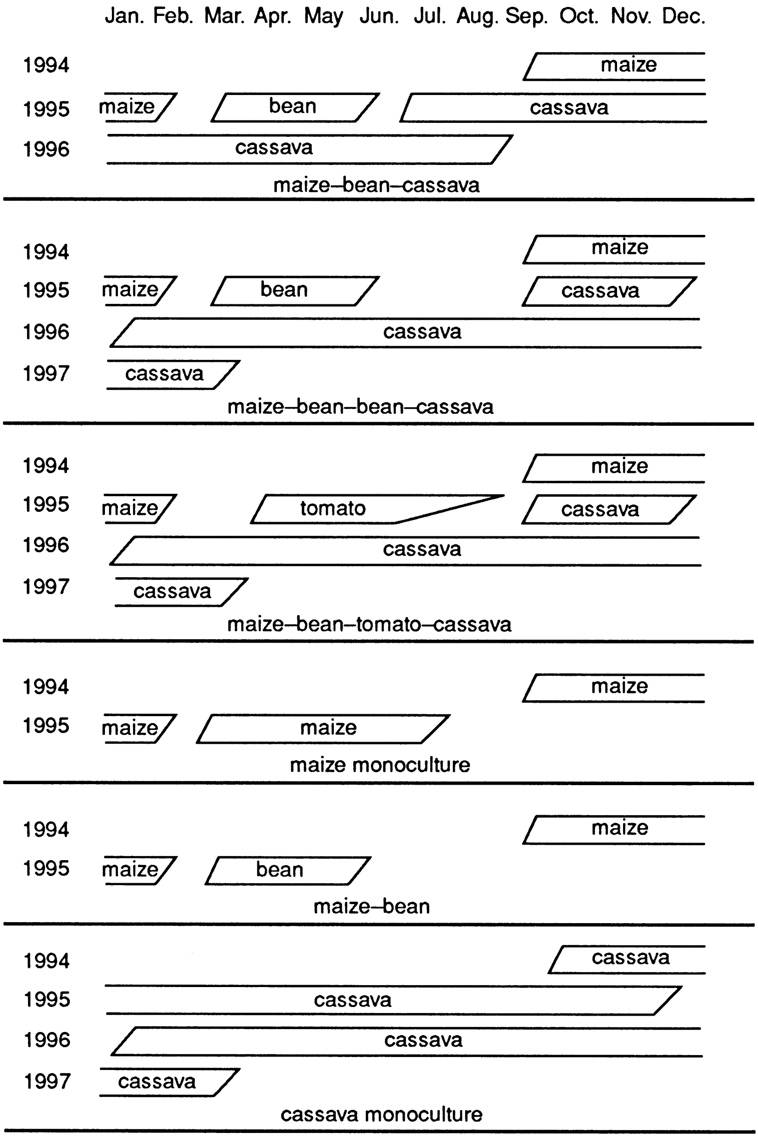

Fig. 2. Cropping patterns included in farm scenarios.

Matthews and Hunt (1994) described an earlier Pascal version of CropSim CASSAVA. Predictions of response to temperature and photoperiod in Australia and to water stress in Colombia were generally good. Unfortunately, CropSim CASSAVA does not include a plant nitrogen submodel; it simulates the soil nitrogen balance but not plant response.

The limited on-farm harvest data suggested that the maize and bean models overestimated yields and underestimated year-to-year variability. The crop models did not address soil phosphorus availability or root-knot nematodes

(*Meloidogyne incognita* and *M. hapla*, Mullin *et al.*, 1991), both of which were important constraints to crop production in the region. Recovery factors (Table 3) corrected for over prediction of yields.

### *Farm simulation*

The Farming System Simulator (FSS) used in this study was developed as a tool for characterizing farm sustainability (Hansen, 1996a, Hansen *et al.*, 1996). It could simulate a replicated farm scenario with stochastic inputs of weather and prices. During each simulation year, FSS first forecasted monthly prices (Equations 6 and 7). Then for each field, FSS called crop models to simulate the effects of weather patterns, soil dynamics and management on crop production for each crop and fallow period, and stored information about field events in an event queue. Monthly events that simulated fixed cost accounting and household consumption were added to the event queue, along with any additional scheduled operations. The event queue then executed accumulated events and checked for conditions for farm failure after each event. Failure was indicated by insolvency: the inability to cover fixed costs, scheduled loan payments or household subsistence consumption in a particular month. If event execution failed, the failure was recorded and the current replicate was suspended. All changes in resource balances occurred in response to events.

FSS simulated 100 replicates of each farm scenario. The model farming system had the same initial state but different realizations of weather and prices in each replicate of a given scenario. All scenarios used the same sample of price and weather realizations. FSS recorded minimum, 25th percentile, median, 75th percentile and maximum supply of liquid assets (that is, monetary reserves plus the value of all stored harvest products) among replicates at the end of each simulation year, the value of each resource each year for each continuing replicate, and the occurrence and timing of failures.

## RESULTS

### *Base scenario*

Simulated sustainability, $\hat{S}(15)$, of the *base* scenario was 0.64 (s.e.$_{\hat{S}}$ 0.048) at the end of 15 years. Since the *base* scenario required certain assumptions that were difficult to validate, this value should not be interpreted as a predicted probability that the actual farm will continue for at least 15 years. Instead, it was a standard for comparing alternatives and for testing the effects of hypothesized constraints to sustainability of the model farming system within its model environment. The cumulative distribution of liquid assets broadened and the probability of failure (the $y$-axis in Fig. 3) increaseed as the scenario progressed (Fig. 3). Figure 4 shows the resulting $\hat{S}(t)$ as a decreasing function of time.

### *Cropping systems*

The most sustainable simulated rotation of the three traditional crops was the

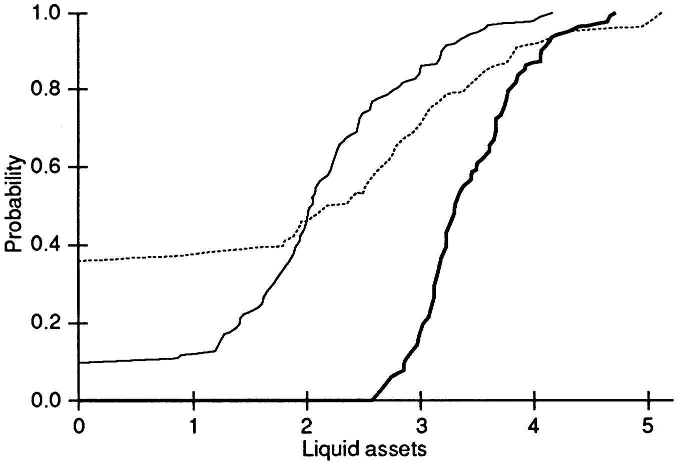

Fig. 3. Cumulative distribution of liquid assets (Col$, millions) for the *base* scenario after one (—), six (—) and fifteen (·····) years.

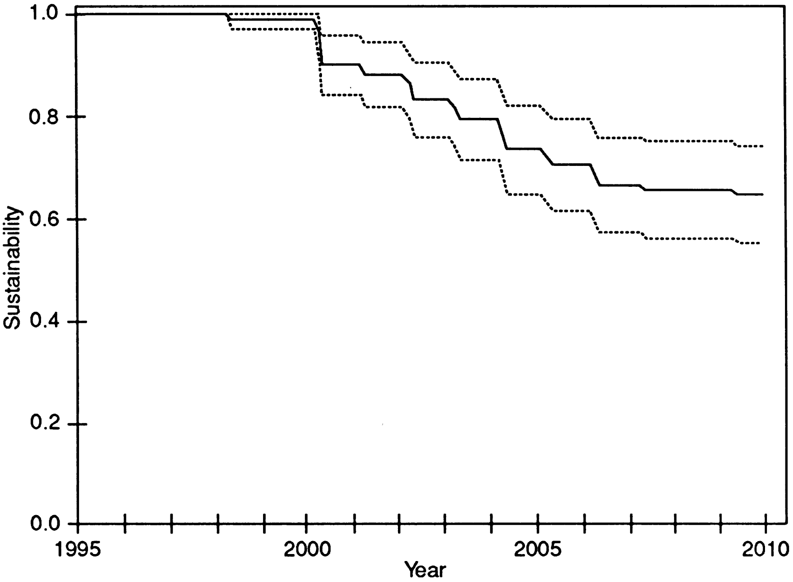

Fig. 4. Predicted sustainability $S(t)$ (—), and 95% confidence limits (·····) as a function of time simulated for the *base* scenario.

two-year maize–bean–cassava rotation (Table 10). It was also the most intensive rotation simulated, with little fallow time. Incorporating irrigated tomato into the *base* scenario resulted in an even higher sustainability. *Maize monoculture* was the least sustainable annual cropping system. These results (Table 10) supported the hypotheses that farm sustainability is dependent on cropping system, and that incorporating a high value, irrigated crop (tomato) into a rotation of traditional

Table 10. *Predicted 15 year sustainability* ($\hat{S}(15)$) *of cropping system scenarios, and McNemar* ($G_{P,adj}$) *and G-test* ($G_{I,adj}$) *statistics for difference from the* base *scenario*

| Scenario | Hypotheses† | $\hat{S}(15)$ | s.e.$_{\hat{S}}$ | $G_{\mathrm{P,adj}}$ | $G_{\mathrm{I,adj}}$ |
|---|---|---|---|---|---|
| Maize–bean–bean–cassava (base scenario) | all | 0.64 | 0.048 | —‡ | —‡ |
| Maize–tomato–bean–cassava | 1, 3 | 0.99 | 0.010 | 41.9** | 49.0** |
| Maize–bean–cassava | 1 | 0.95 | 0.022 | —§ | 32.1** |
| Cassava monoculture | 1, 2 | 0.47 | 0.050 | 8.6** | 5.8* |
| Maize–bean | 1 | 0.04 | 0.020 | 75.3** | 91.4** |
| Maize monoculture | 1, 2 | 0.00 | 0.000 | —§ | —§ |
| Coffee @ 2.50 t ha$^{-1}$ | 1, 4 | 0.99 | 0.010 | —§ | 49.0** |
| Coffee @ 2.25 t ha$^{-1}$ | 1, 4 | 0.92 | 0.027 | 24.7** | 24.0** |
| Coffee @ 2.00 t ha$^{-1}$ | 1, 4 | 0.70 | 0.046 | 1.0 ns | 0.8 ns |
| Coffee @ 1.75 t ha$^{-1}$ | 1, 4 | 0.30 | 0.046 | 26.5** | 23.5** |

†hypotheses are listed in Table 5; ‡comparison does not apply to the *base* scenario; §undefined; $*p = 0.05$; $**p = 0.01$; ns = not significant.

crops enhances farm sustainability. However, the results did not support the generalization that diversified crop rotations consistently contribute to a more sustainable farming system than do monocultures. Although the three most sustainable annual cropping systems were diversified rotations, sustainability of the *cassava monoculture* was higher than that of the *maize–bean* rotation.

Results of the coffee scenarios (Table 10) supported the hypothesis that sustainability of a farm in coffee monoculture is positively related to coffee yields. Coffee production was significantly more sustainable than the *base* scenario when annual yields were at least 2.25 t ha$^{-1}$. Coffee is expected to produce annual yields of about 2.0–2.5 t ha$^{-1}$ in the region of the study farm.

### *Nitrogen management*

Increasing nitrogen fertilizer use on beans and maize by 100% and reducing its use by 50% both reduced simulated sustainability (Table 11), supporting the hypothesis that either excessive or insufficient nitrogen fertilizer reduces sustainability of the study farm. Reducing the applied nitrogen diminished sustainability by reducing crop yields, while increasing its application reduced sustainability by increasing costs. The level of applied nitrogen did not result in discernable long-term trends associated with the buildup or depletion of soil nitrogen (Hansen, 1996a).

### *Costs and prices*

Increasing the price that the farmer receives for crops or reducing the price of material or labour inputs improved sustainability, supporting the hypotheses that low prices for crop products, high material input prices and high wages for hired labour constrain farm sustainability. However, sustainability was more sensitive

Table 11. *Relative sensitivity* ($\lambda$) *of predicted 15 year sustainability* ($\hat{S}(15)$) *to continuous factors, and McNemar* ($G_{P,adj}$) *and G-test* ($G_{I,adj}$) *statistics for difference from the* base *scenario*

| Factor | Hypothesis† | Base | Adjusted | $\hat{S}$ (15) | s.e.$_{\hat{S}}$ | $\lambda$ | $G_{\mathrm{P,adj}}$ | $G_{\mathrm{I,adj}}$ |
|---|---|---|---|---|---|---|---|---|
| Area cultivated (ha) | 11 | 2.34 | 2.57 | 1.00 | 0.000 | 5.72 | —‡ | —‡ |
| Mean commodity prices§ | 6 | 100% | 110% | 0.98 | 0.014 | 5.31 | —‡ | 43.6** |
| Subsistence consumption (million Col$ $a^{-1}$) | 9 | 2.75 | 2.48 | 0.97 | 0.017 | 5.25 | —‡ | 39.1** |
| Material input prices§ | 7 | 100% | 80% | 0.80 | 0.040 | 1.25 | —‡ | 6.4* |
| Hired labour wages§ | 8 | 100% | 80% | 0.79 | 0.041 | 1.17 | —‡ | 5.5* |
| Discretionary consumption (% liquid assets $a^{-1}$) | 10 | 20% | 16% | 0.78 | 0.041 | 1.09 | 14.6** | 4.7* |
| Initial funds (million Col$) | 12 | 4.00 | 4.40 | 0.69 | 0.046 | 0.78 | 3.9* | 0.6 ns |
| Nitrogen fertilizer (kg N $ha^{-1}$ $a^{-1}$)¶ | 5 | 25.0 | 50.0 | 0.49 | 0.050 | −0.23 | 10.6** | 4.6* |
| Nitrogen fertilizer (kg N $ha^{-1}$ $a^{-1}$)¶ | 5 | 25.0 | 12.5 | 0.29 | 0.045 | −1.09 | 41.9** | 25.0** |

†hypotheses are listed in Table 5; ‡undefined; §percentage of *base* scenario; ¶average among the three phases of rotation, *$p$ = 0.05; **$p$ = 0.01; ns = not significant.

to crop prices than to input prices (Table 11). Sensitivities to material input prices and to the price of labour were similar. Reducing household expenditures also improved sustainability, supporting the hypotheses that a high subsistence spending requirement and a high level of discretionary spending constrain sustainability. Simulated sustainability was much more sensitive to subsistence requirements than to discretionary spending.

### *Resources*

Increasing the total land area under cultivation by 10% increased simulated sustainability to 1.0 (Table 11), supporting the hypothesis that access to land constrains farm sustainability. Although this suggested that the total area cultivated was an important determinant of farm sustainability, the crop models did not account for the impacts on crop production of slope steepness, loss of topsoil phosphorus from previous erosion, or competition from perennial grasses on the land that was in grass fallow. The farmer considered these factors in his decision not to cultivate this area.

Although results supported the hypothesis that limited initial savings constrain farm sustainability, the initial supply of cash was much less important than the land area cultivated (Table 11). Access to Col$ 2 000 000 of credit at an interest rate of 19% improved sustainability a small but significant amount. Increasing the amount of available credit to Col$ 3 000 000 did not improve sustainability further. However, reducing the interest rate to 9.5% did improve sustainability. These results supported the hypotheses that access to credit enhances farm sustainability, and that farm sustainability is negatively related to loan interest rates. They did not support the hypothesis that increasing the credit supply increases farm sustainability.

Table 12. *Predicted nine-year sustainability* ($\hat{S}(9) \pm s.e._{\hat{S}}$), *McNemar test statistic* ($G_{P,adj}$) *for difference from the* base *scenario, and standard deviation of liquid assets after three years* (s) *for source of risk scenarios*

| Scenario | Hypothesis† | $\hat{S}(9) \pm s.e._{\hat{S}}$ | $G_{P,adj}$ | $s$ |
|---|---|---|---|---|
| Base | | 0.79 ± 0.040 | —‡ | 699 504 |
| No weather risk | 16 | 0.85 ± 0.035 | 1.2 ns | 659 063 |
| No price risk | 16 | 1.00 ± 0.000 | —§ | 181 131 |
| Not diversified | 17 | 0.10 ± 0.030 | 106.2** | —¶ |

†hypotheses are listed in Table 5; ‡comparison does not apply to the *base* scenario; §undefined; ¶not determined because the distribution was truncated by failures.

### *Sources of risk*

Results (Table 12, Fig. 5) supported the hypotheses that weather and price variability contribute unequally to whole-farm risk and the probability of failure, and that spatial diversification reduces farm risk and enhances sustainability. Prices contributed much more to farm risk than weather in this environment, although the crop models may have underpredicted production risk due to weather. Results of the *no spatial diversification* scenario confirmed the hypothesis that spatial diversity reduces farm risk and enhances sustainability. Although the maximum value of liquid assets was much higher when the entire farm was planted in the same phase of rotation, a very high probability of failure resulted compared with the *base* scenario at three or nine years (Fig. 5b and c). An important observation was that farm risk was reduced by diversification in space, but not by diversification in time. The *no spatial diversification* scenario followed the same temporally diversified rotation as the *base* scenario.

### *Ranking constraints to sustainability*

Table 11 lists the factors that can be represented as continuous quantities, and ranks their importance as constraints to sustainability. The factors that had a direct, proportional impact on farm income or expenses, that is, land area cultivated, subsistence consumption, and mean commodity prices, had the greatest impact on simulated farm sustainability. Input prices, wages, discretionary consumption requirements and initial funds also constrained sustainability significantly. Although sustainability was quite sensitive to changes in cropping system (Table 10), relative sensitivity to continuous factors cannot be compared with absolute sensitivity to discrete factors such as cropping system.

## DISCUSSION

This study demonstrates the usefulness of long-term, stochastic simulation of a farm model for integrating the effects and evaluating the importance of a diverse set of determinants of sustainability. This type of simulation study requires data

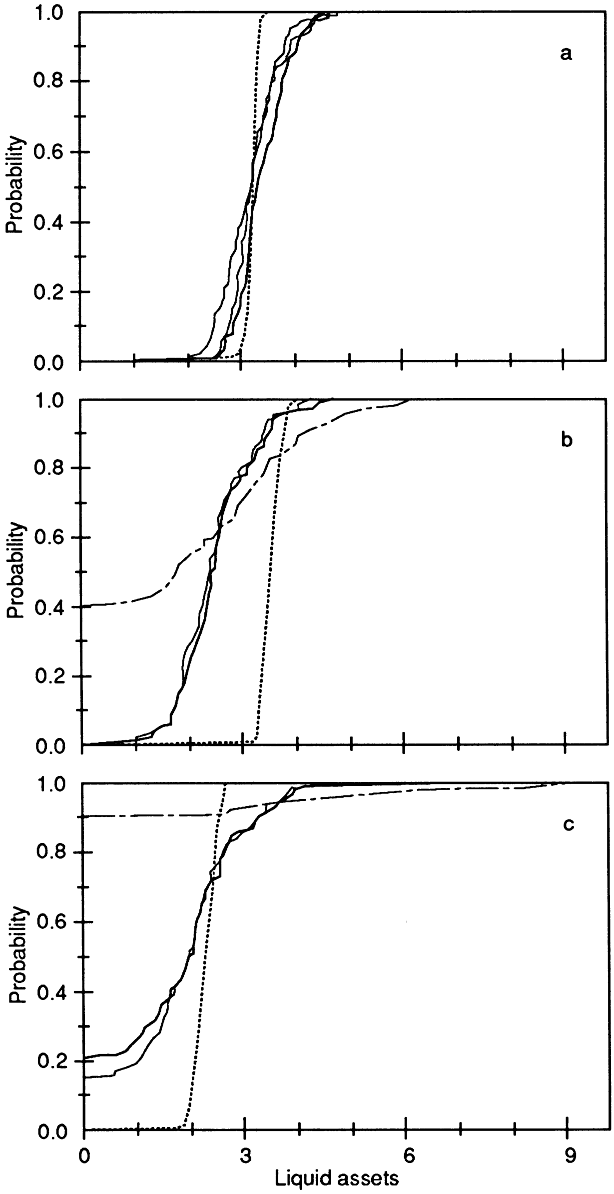

Fig. 5. Cumulative distribution of liquid assets (Col$, millions) for the source of risk scenarios (*base* scenario, —; *no weather risk*, —; *no price risk*, . . . . .; no spatial diversion, – · – · –) after one (a), three (b) and nine (c) years.

that are difficult to measure (for example, household spending habits and minimum subsistence requirements) and assumptions that are difficult to validate (for example, that the trend and statistical properties of future prices will match past behaviour). As sustainability deals with the future behaviour and fate of agricultural systems, its assessment will necessarily entail assumptions that are difficult to validate. The assumptions required by this simulation study are clearly more defensible than predictions based on extrapolation of past system behaviour, estimates of system resilience, the presence or absence of 'sustainability indicators', or adherence to prescribed approaches (Hansen, 1996b).

This study has important practical implications for the farmer, researchers and policy makers. It suggests that the farmer might enhance the sustainability of his farm by intensifying and diversifying production of annual crops and by including tomato or other highly valued vegetables in crop rotations. On-farm agronomic research could reduce the uncertainty associated with changing cropping systems. Agronomic trials combined with market research might identify other promising highly valued vegetable crops. Results show that farm risk in this environment is influenced much more by prices than by weather variability. Policies that reduce price volatility can be expected to enhance farm sustainability. Policy makers must, however, balance the needs of small-scale farmers with those of other segments of society.

Several limitations should be considered when applying the results of this study. First, we were unable to measure and therefore had to assume values for several important model parameters, particularly those related to household consumption. Second, evidence suggests that the crop models generally overpredict yields, underestimate year-to-year variability, and do not consider some yield-reducing stresses that are important in this environment (Hansen, 1996a). Third, FSS does not account for within-season resource constraints and, finally, FSS does not simulate adaptive management of farming enterprises, but imposes fixed management.

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