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Can Sustainability Be Quantified? *

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"No human investigation can be called real science if it cannot be demonstrated mathematically."

Leonardo da Vinci

"To be measured scientifically, sustainability must have a precise and unambiguous definition. It can safely be said that agreement on such a definition does not yet exist."

J.K. Lynam and R.W. Herdt

Concern and conviction

Taken together, the quotations heading this paper answer the question in its title. Sustainability can be quantified and indeed must be quantified; but quantification depends on definition. The word "sustainability" was coined several years ago and is now common currency, but the subject lacks a methodology and its burgeoning literature is conspicuously deficient in measurements. In a collection of abstracts from 250 papers concerned with sustainable agriculture (Carls 1989), less than 10% contain a figure for production and less than 5% a figure for the state of a resource base. Virtually none of the abstracts refer to trends in production as related to trends in resources which are central to the assessment of sustainability.

Does this matter, provided everyone is sensitive to the concern for posterity which is the driving force of our search for sustainable systems of agriculture? I believe it does. Sustainability is too important an issue to be left in the Natural History stage of evolution. If proper weight is to be given to the balance be-

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tween sustainability, efficiency, and equity; if attempts to establish sustainable systems of production are to be sharply focussed; if priorities for research are to be rationally assigned; if the implications of that research are to be effectively disseminated and applied, then there is an urgent need to move the subject as rapidly as possible from Natural History to Natural Philosophy. What follows is an attempt to encourage that process. The ideas I advance may prove to be flawed or impractical but I shall rest content if they catalyse others to develop better quantitative tools.

Search for a definition

The primary objective of research on sustainable systems of agriculture is to make better forecasts of their behaviour. A specification of sustainability should therefore include a time scale or at least a reference to some undefined period such as "the foreseeable future". Future behaviour can rarely be assessed without reference to how the system, or others like it, have performed previously. But there are statistical reasons why the immediate past may be an uncertain guide, as we shall see later. In some cases it is possible to base judgement on sound quantitative evidence; in others, attempts to predict sustainability will be little better than guesswork.

Because of the difficulty of framing a definition for sustainability that is both generally valid and acceptable to workers in different disciplines, most published definitions are more qualitative than quantitative. For example, the Technical Advisory of Committee of the Consultative Group on Internaitonal Agr cultural Research (TAC 1988) states that "sustainable agriculture should involve the successful management of resources ..... to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources."

Lynam and Herdt (1988) were more direct and more specific: ".... a sustainable system is one with a non-negative trend in measured output." But by the profligate use of inputs, it would be possible to achieve increases in output despite damage to the resource base. This point is covered by the suggestion of Lynam and Herdt (LH) that output should be defined as "the total value (at standardized prices) of all output from the system over one cycle divided by the total value of all inputs ...." A sustainable system is then identified by a non-zero trend in this ratio, referred to as "total factor productivity."

In practice, the "total value of all inputs" will often be a somewhat arbitrary quantity with diverse components whose relative value is hard to assess. Morover, in the terminology of the biological and physical sciences, the ratio of an output to an input is an efficiency; and to add to the semantic confusion, agronomists often use "productivity" in place of "yield" - straight output and not output per unit input. It is desirable that the sustainability of an agricultural system should be clearly distinguished from its

efficiency, because the two indices of performance are not always correlated. In intensive agriculture, misguided attempts to increase efficiency as well as reducing risk (by overusing chemicals for example) have made systems unsustainable.

Can any more rational way be found of relating sustainability to inputs and outputs? To be sustainable, a system of production or distribution must reconcile two characteristics: benefits derived from the system should be maintained, in practice from year to year and in principle from generation to generation; and the system itself should not deteriorate as a consequence of exploitation. These criteria can be summarized succinctly: A **system is sustainable over a defined period if outputs do not decrease when inputs are not increased.** Table 1 explores the logical implications of this definition and others are considered in the following notes.

(i) Although the definition makes no explicit reference to degradation of the environment, it carries the implication (as does LH) that output could not be maintained in a system damaging the environment unless the adverse effects of degradation were compensated by deliberately increasing inputs. For example, loss of production through soil erosion could conceivably be offset, at least for a limited period, by using more fertiliser.

(ii) Because the definition is quantitative but not specific, it appears to be more versatile than LH. For example, output can be defined in terms of yield expressed as biomass, energy, protein, etc.; or in economic terms such as income or livelihoods. Likewise inputs can be physical, biological, or economic. However, both inputs and outputs must be referred to the same base, eg. a region, unit land area, or unit consumer. To compare trends expressed in different units or even in different entities, it is convenient to work with relative trends which have the physical of 1/TIME/

(iii) The definition allows sustainability to be quantified in terms of a non-negative trend in outputs observed when the trend in all relevant inputs is non-positive. However, to assess sustainability in an experimental trial, inputs should not change with time in which case my criterion for sustainability is effectively the same as LH.

(iv) The main disadvantage of the definition (shared with LH) is that unless detailed information about input/output relation is available, it cannot be used to establish whether a system is sustainable when its output increases with time in response to an increase of input with time. Unlike LH, however, the definition implies a lack of sustainability whenever output decreases, even when associated with a decrease of inputs (Table 1). This is the point where current emphasis on sustainability in countries with stable populations and food surpluses differs markedly from the emphasis in countries with chronic shortages of food coupled with rapidly expanding populations. For the latter countries, a decrease in food

Table 1. Logic table for sustainability

Outputs	Inputs	Status
Decreasing	Decreasing	Indeterminate
	Constant	Unsustainable
	Increasing	Unsustainable
Constant	Decreasing	Sustainable
	Constant	Sustainable
	Increasing	Unsustainable
Increasing	Decreasing	Sustainable
	Constant	Sustainable
	Increasing	Indeterminate

Table 2. Land use and population for two districts in northern Andhra Pradesh

	Area (10^3 km^2)					Rural Population (million)		Population Density (km^{-2})	
	Gross	Net Cropped		Cereal					
Year		1959	1978	1959	1978	1961	1981	1962	1982
Adilabad	16.2	5.2	5.9	2.9	3.2	0.87	1.35	52	83
Karimnagar	11.9	4.7	4.9	3.1	3.9	1.53	2.08	129	175

production is always unsustainable to the extent that it postpones the time when "basic human needs" can be satisfied.

To summarize, once "sustainability" has been defined it can be quantified. Once quantified, it can be estimated from a shrewd assessment of historical evidence. The important intermediate step of making the definition operational will now be considered.

For crops, output is conventionally specified in term of yield Y (t ha^{-1}) or prodution YA (t) from a defined area A (ha). If the population density of the defined area is P (ha^{-1}), the production per caput is

$$C = Y\,A/P \qquad (1)$$

Differentiation gives the relation between the instantaneous fractional rate of change of these quantities as

$$(dC/dt)/C = (dY/dt)/Y + (dA/dt)/A$$
$$(dP/dt)/P \qquad (2)$$

where dC/dt, etc., are total derivatives of the variables with respect to time. Note the convenience of expressing trends in fractional form so that they can be added. Over any period t in which a derivative is constant, it can be replaced by a finite difference of the form $\Delta C/\Delta t$. The analysis could be taken further by using partial derivatives to account for the dependence of Y on A (e.g. as a result of bringing marginal lands under the plough) or of Y on P (as the result of introducing new technology in response to population pressure.)

In principle, the first step in assessing sustainability for a system of crop production should be to estimate the trend in production per unit area (dY/dt)/Y or per caput (dC/dt)/C. In practice, this is rarely a straightforward exercise. To explore difficulties, I shall consider how trends can be determined, first from records of regional production and then from long-term trials.

District analysis

Areas under specific crops, yields and production are available for disticts in India. Adilabad and Karimnagar in northern Andhra Pradesh, with records for the period 1956 to 1983, were chosen for this analysis because of a strong contrast in their behaviour (Table 2). Rural populations were available from censuses in 1971 and 1981.

Following the implementation of the Sri Rama Sagar scheme in Karimnagar, the area under irrigation (mainly paddy) has increased from 30% to about 45% of the cultivated area since the early 1950s and a corresponding increase of production has outstripped the increase in rural population at 1.5% per year. In neighbouring Adilabad, with a forested area of 43% compared with 23% in Karimnagar, production has also increased but more slowly than the population (2.2% per year).

For the production of cereals (mainly rice, sorghum and maize) over the whole period, plots of Y (Fig. 1) and of A against year exhibit scatter generated by

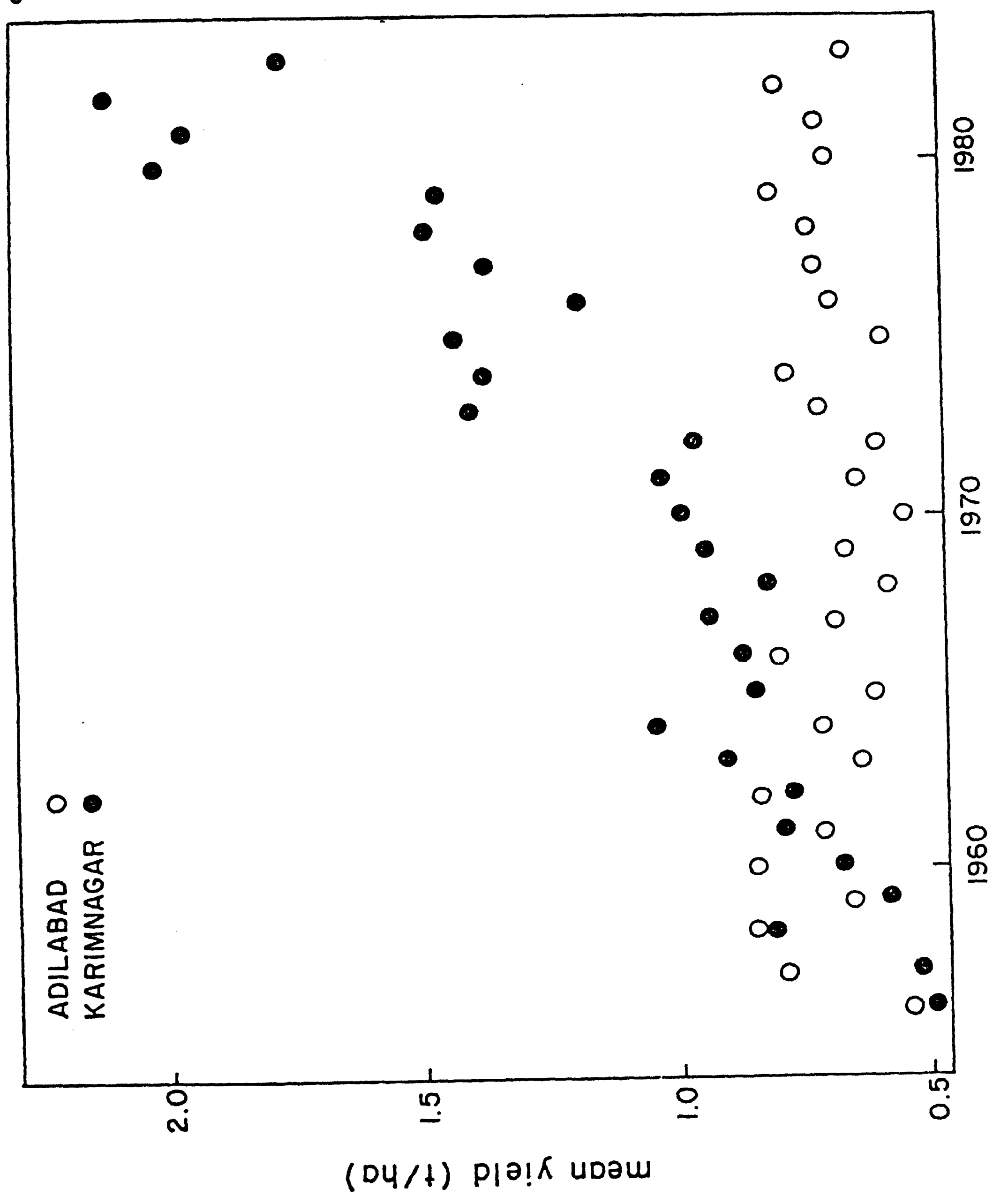

Fig. 1 Average yield of major cereals for Adilabad and Karimnagar districts in Andhra Pradesh, 1956-1983.

differences in weather from season to season as well as by errors that are inevitable when records are collected over large areas. For some periods, the scatter was so large that no clear trend could be identified but when a trend was clear, it did not change much over the period of the record. Linear regressions were therefore estimated for yield (Y), for area (A), and for production (YA). Population was assumed to increase exponentially but the increase was small enough to allow linear regressions to be fitted to A/P and to (YA)/P, the area and production per caput. For production, the CV obtained from the regression analysis was about 11% in Adilabad and about 17% in Karimnagar.

Table 3 summarizes conclusions from this analysis. In both districts, the area of cereal production increased by less than 1% (of the mean value for the period) per year. Yield in Karimnagar increased throughout the period (Fig. 1) in contrast to a very small (and non-significant) downward trend in Adilabad. Production per caput decreased by more than 1% per annum in Adilabad (Fig. 2) but in Karimnagar, because of the strong upward trend in yield, it increased by 3.5% per year (Fig. 3).

The analysis highlights two major problems in attempting to assess the sustainability of an agricultural system from this type of record.

First, using a 28-year record has the advantage of establishing the mean values of long-term trends in yield and production with acceptably small errors (about ± 10% for Karimnagar where the trend is most consistent). In assessing sustainability, however, it is more important to establish trends over the recent past - say, over 5 to 10 years. The lower parts of Figs. 2 and 3 show that when the analysis was restricted to the period 1979-83, the error in estimating the yield trend was of the order of ± 100% for both districts.

In this example, a record of at least 10 years is needed to reduce to an acceptable level the uncertainty generated by random year-to-year fluctuations. Increasing the regression period in 5 year steps clearly showed that the upward trend in yield for Karimnagar was consistent; but in Adilabad, an initial upward trend of 1 to 2% per annum was reversed and the figure for the last 5 years is -2.9 ± 3.6%. Analysts are therefore faced with a dilemma: to assess sustainability on the basis of recent trends in yield which are very uncertain; or to rely on a more precise long-term measurement which may have ceased to be relevant!

The second problem is the indeterminate nature of sustainability when both output and input are increasing (Table 1). Cereal production in Adilabad is clearly unsustainable in terms of consumption (-1.3% per year over 28 years and -5.1% over the last 5 years) and may even be unsustainable in terms of land area. In Karimnagar, the suply of cereals is more secure but whether or not it is sustainable in terms of my definition cannot be determined because imputs must have increased substantially to sustain such a

Table 3. Mean values of area for cereal cultivation, yield and production in Adilabad and Karimnagar Districts, 1956-1983.

Quantity Measured	Mean		Fractional Rate of Change % per year	
	Adilabad	Karimnagar	Adilabad	Karimnagar
Area (10^3 ha)	309	324	0.81 ± 0.11	0.6 ± 0.2
Yield (kg ha^{-1})	698	1125	-0.05 ± 0.30	4.5 ± 0.4
Production (10^3 t)	215	372	0.79 ± 0.31	5.0 ± 0.5
Derived				
Area (ha per caput)	0.302	0.189	-1.33 ± 0.10	-0.92 ± 0.22
Production (ha per caput)	211	208	-1.42 ± 0.34	3.51 ± 0.42

(In the type of analysis used, the product of mean area and mean yield is not necessarily identical to the mean production. The sum of the fractional rates of change of area and yield is approximately equal to the fractional rate of change of production as shown by equation 2.)

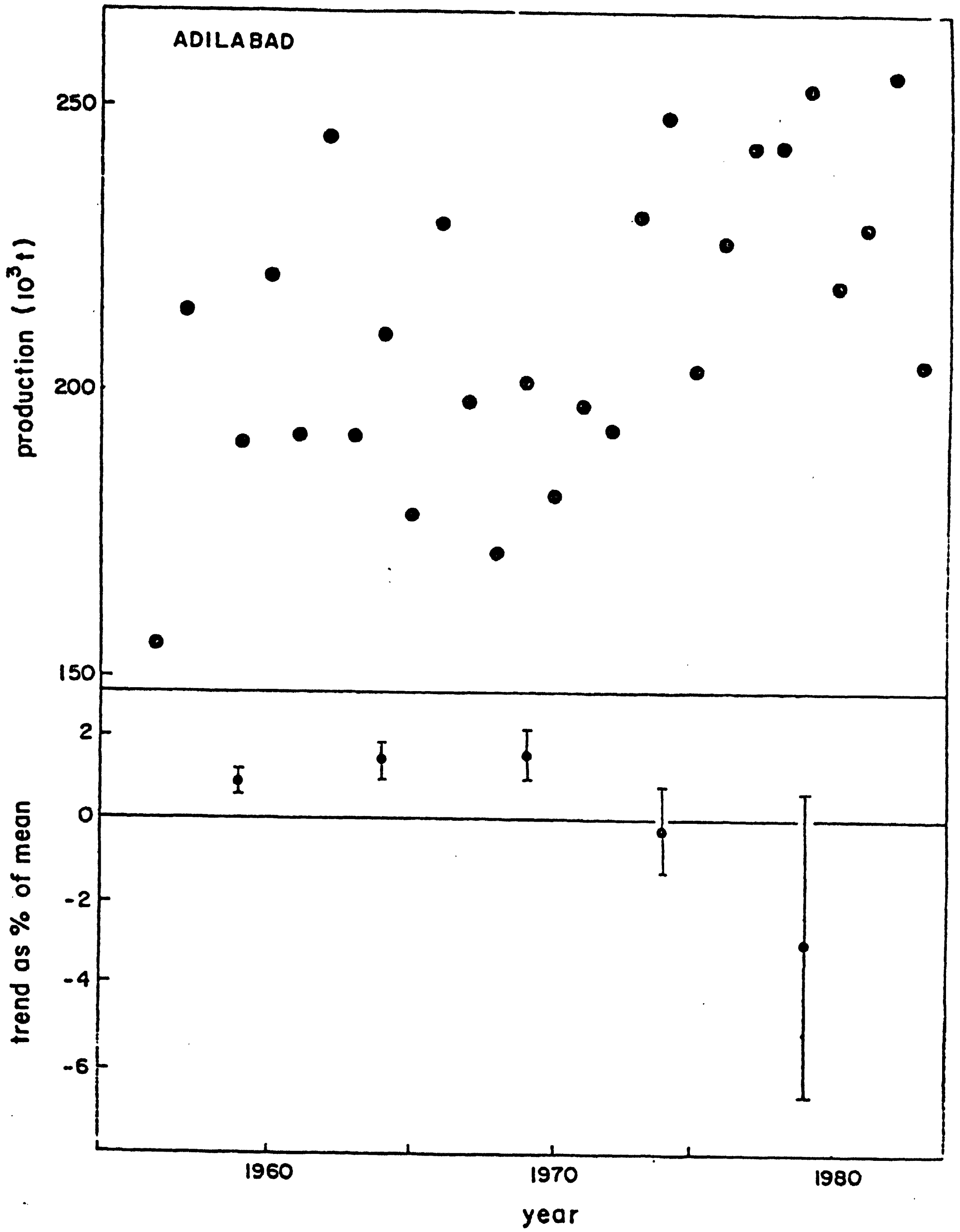

Fig. 2 Upper, Production of major cereals in Adilabad district for 1956-1983. Lower, Trends in production estimated as fractional changes over the period from 1983 to the date on the axis, i.e. for periods ranging from 5 to 25 years.

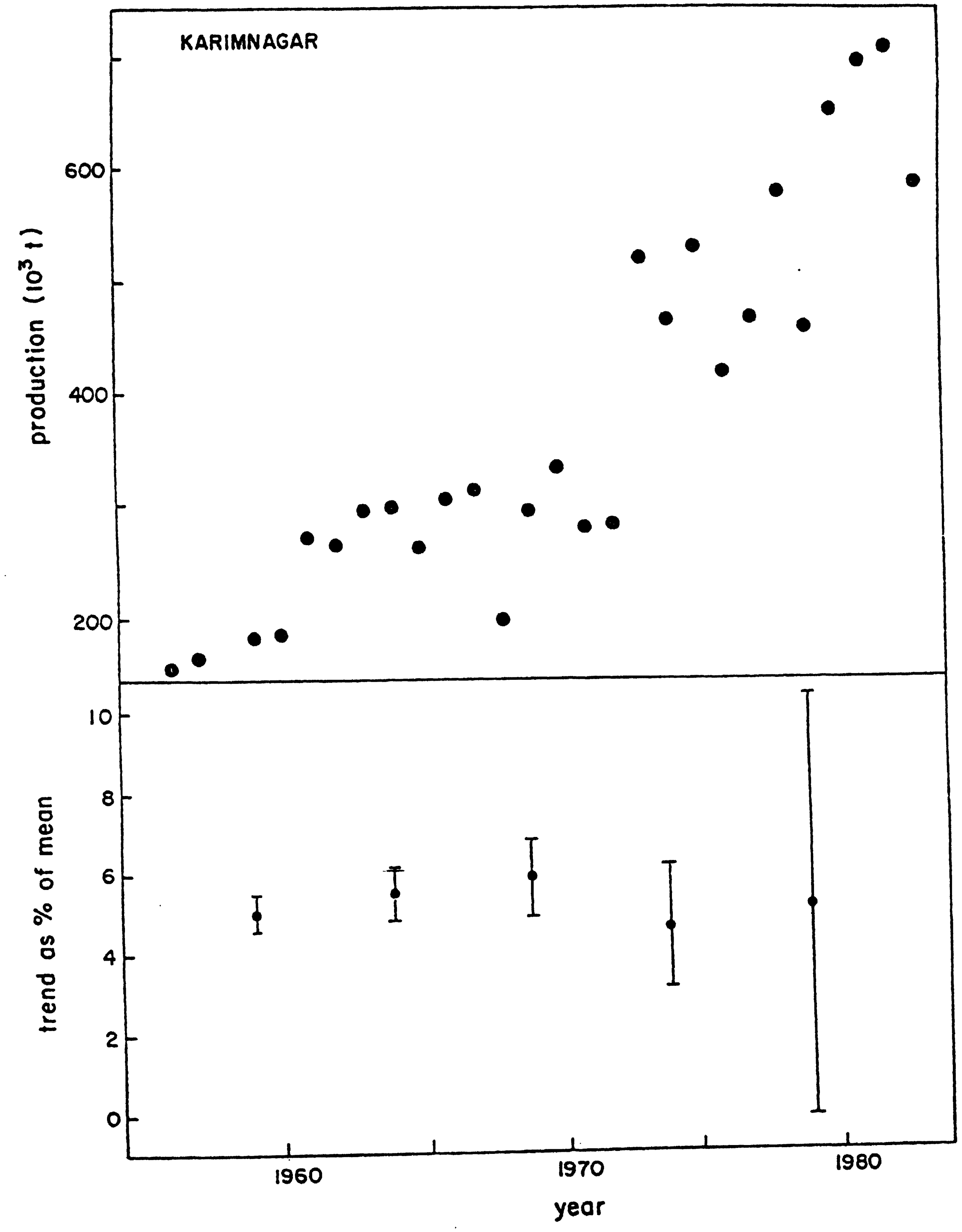

Fig. 3 Data for Karimnagar presented as in Figure 2.

consistent increase of yield. This increase could be enough to conceal the impact on yield, of damage to the environment in the form of erosion, salinity, build up of pests and weeds, etc. The possibility of insidious losses of sustainability in such circumstances calls for constant vigilance on the part of farmers, as well as extension and research agencies.

Long-term experiments

Some of the problems that emerge when trends in yield or production are determined for a whole district do not exist when records are available from a well-maintained long-term trial at a research station. In such trials, inputs are usually held constant in at least one treatment so that the sustainability of the system can be established by measuring the trend in yield. This is still not a trivial problem fields. For example, on the Vertisol watershed at ICRISAT Center, yields of sorghum and maize for the period from 1976 to 1988 had a CV of 20% on high input output for traditional cultivars and cultivation practised on the site.

Long-term trials are usually designed to provide two types of information: (1) changes of yield from year to year in responses to water, damage by pests, etc., (2) measurements of factors likely to be responsible for these changes, e.g. soil pH, nematode populations. As a third type of output, it would also be worth trying to identify an index of the trends in production less susceptible to weather than yield. Soil organic matter has been suggested as a candidate to explore. An index performing consistently would allow confident conclusions to be drawn about likely trends in yields sooner than would be possible from the yields themselves.

Because attempts to quantify sustainability cannot be successful unless uncertainties in trends are properly treated, I now present analysis that determines how many sequential measurements are needed to determine a trend within specified limits of accuracy.

Trend errors and sample

Suppose that an index of production X, measured at regular intervals, changes on average by a fraction f of its original value X(0) during each interval. (For sustainability, f >= 0). After t measurements, the expected value of X is

$$X(t) = X(o)\,(1 + f\,t) \qquad (3)$$

Measurments of X will depart from the value predicted by equation 3 because of changes in the environment. Provided these deviations fit a normal distribution with standard deviation S(X), the standard deviation of the estimated trend f is given by regression theory as

$$S(f) = \frac{S(X)/X(o)}{(\Sigma(n^2) - (\Sigma n)^2/t)^{1/2}} \qquad (4)$$

where n is the sequential number of the measurement.

Because values of n define the series 1, 2, ... t, the difference between the two terms in the denominator reduces to $((t^3 - t)/12)^{1/2}$ which is within 3% of

$t^{3/2}/(12)^{1/2}$ when t exceeds 3. Equation 4 can therefore be written

$$S(f) = 3.46\ (S(X)/X(o))/t^{3/2} \qquad (5)$$

This equation can be manipulated to find the number of measurements that would be needed to obtain S(f) as a specified fraction of the trend f when the CV of the measurements, defined here as S(X)/X(o), is known. For example if it is stipulated that S(f) must not exceed f/3, there is a 68% chance that the true value of f falls between 0.67 and 1.33 of the estimate. Then replacing S(f) in equation 5 by f/3 and solving for t gives

$$t = (10.4\ CV/f)^{2/3} \qquad (6)$$

For annual observations, the required number of years is t-1 assuming the first observations is made when t = 0. The trend f is the change of X in one year expressed as a fraction of its initial value. In Fig. 4, values of t-1 in years are shown as a function of the trend f and of the CV.

The condition S(f)=f/3 is identical to 3S(f) = f. Equation 6 and Fig. 4 therefore give the number of years at which f can be determined within the limits f ± f with a probability corresponding to three times the standard deviation or 99.7%. This implies that the sign of f can be established with 99.7% probability.

When crop yields are reported annually, either as an average for a district (as in this paper) or as the value from a single experimental plot, value being associated with erratic year to year differences in rainfall or some other limiting element of climate. It appears that for a trend of 0.1 (10%) per year, a record of 15 to 25 years would be needed to determine a trend within the stipulated limits and with 68% probability.

Values of CV between 5 and 10% might be obtained from sequential measurements of a soil property such as organic carbon or nitrogen status. To achieve the stipulated accuracy, annual observations would need to continue for at least 5 to 10 years if the trend was less than 10% per year and for at least 10 to 15 years if the trend was less than 5% per year.

The analysis can be extended to the more general case of measurements repeated at intervals of m years where m is not necessarily an integer. The number of measurements made in y years is y/m + 1 and the trend, measured as a change in P over m years is mf. Substituting these values in equation 4 yields the expression

$$y = m^{1/3}\ (10.5 \times CV/f)^{2/3} - m$$

If y(m) is the number of years needed to obtain the stipulated accuracy, it is convenient to evaluate the quantity y(m)/y(1) which is the factor by which the values of y(1) obtained from Fig. 1 must be multiplied to obtain y(m). For values of m of practical interest, i.e. from 2 to 5 years, y(m)/y(1) is very close to 1 + 0.15 m. This implies that if m = 5 years, for example, the required number of years will be 1.75 y(1) rounded up to the nearest multiple of 5. In the specific case where f = 0.05

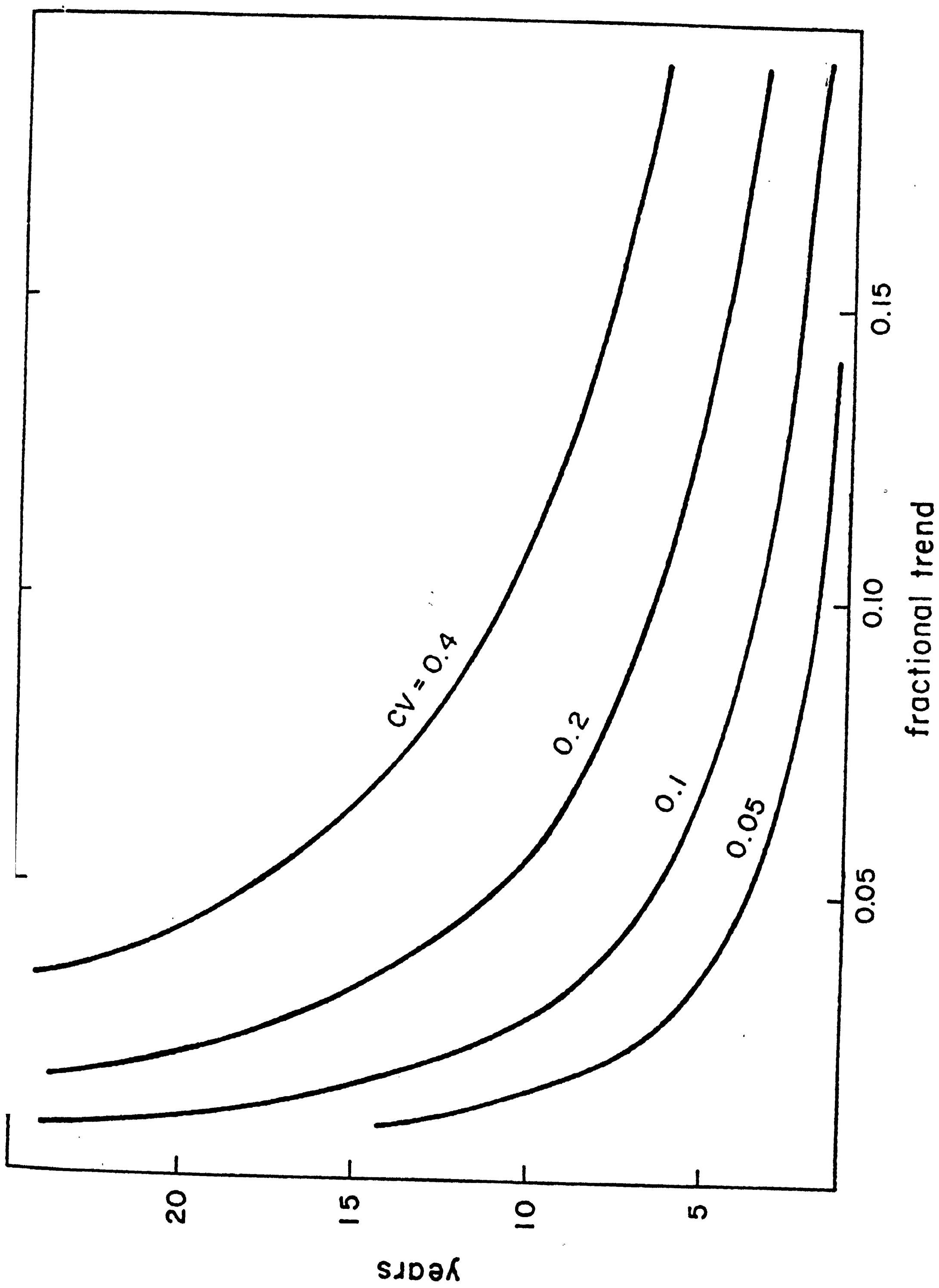

Fig. 4 Number of years needed to establish a constant trend of specified size to within 33% of its true value with a probability of 68%; or within 100% of its true value with a probability of 99.7%. The CV on each curve refers to regression fitted to primary data.

per year and CV = 0.1, y(1) is 7 years from Fig. 4 and y(5) is 12.25 rounded up to 15 years.

When the standard deviation of X is not constant with time but changes in proportion to X, the value of y will be overestimated but the discrepancy will usually be negligible when the change in X is less than 20%.

Much of this analysis is based on the assumption that the trends which emerge from attempts to assess sustainability are likely to be almost constant over the period in which they are determined. This will not always be so. Particular danger lies in accelerating trends where a figure based on historical records will always underestimate the current value. The only way to mitigate this problem is to search diligently for the mechanisms responsible for a trend and for its change with time.

Short-cuts to assessing sustainability

The last section is relevant both to the analysis of district or regional values of production and to the design of long-term field designed to investigate the sustainability of a particular system of production. It is disquieting to find that because estimated CVs are often in the range 20 to 40%, trends in production are unlikely to be reliable unless records extend for 10 to 20 years. Fortunately there are several potential short-cuts to assessing sustainability though none has yet been thoroughly tested.

The first short-cut is the simulation of crop production using models. Models for many major crops have now reached a level of reliability where it should be possible to estimate, with an uncertainty of less than ± 20% what the yield of a crop should be in a given season when weather is the only changing factor. When a major feature of the environment such as rainfall fluctuates widely from year to year, the CV is likely to be large compared with the error in estimating the yield. If the model works well, the difference between estimated and measured yields should have a much smaller CV than the measurements alone. The time needed to establish a trend in yield (caused by changes in environmental factors other than weather) will therefore be reduced.

The second short-cut is remote sensing which will increasingly be used to explore the sustainability of ecological systems in general and of agricultural systems in particular. One major use is likely to be in assessing losses in the area of agriculturally productive land as a consequence of desertification, salinification within irrigation schemes, etc. (Sahai 1988). Several countries are already using remote sensing routinely to provide crop inventories and this type of record can provide a more accurate basis for estimating regional production than conventional ground measurements of area. Estimating yield from seasonal changes of ground cover is more difficult but should eventually make it possible to monitor crop production on the scale of districts, regions, or even globally. The combination of annual estimates of crop area from remote sensing and corresponding yield estimates from models may ultimately prove to be the fastest way of assessing the sustainability in agricultural systems.

Epilogue

"We are living today in a society frightened by what is happening to its environment ..... Progress .... appears to many people to have led either to a situation in which far-reaching technical developments are initiated without adequate understanding of their ramifications, or, worse, to the deliberate acceptance of procedures known to be unsatisfactory simply because they are cheap and easy to implement. The result is a rapid deterioration in the quality of the human environment".

These words were not lifted from the Bruntland Report or from one of the many reviews of sustainability which it generated. They were written over 20 years ago by John Black (1970). I quote them as a reminder that anxiety about sustaining the environment for agriculture and the word "sustainbility" was coined. I am convinced that our progress in making food production more sustainable in the next 20 years depends crucially on our success in converting "sustainability" from a battle-cry for conservationists and agronomists to hard measurements subjected to rigorous analysis.

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