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TIME TRENDS IN CROP YIELDS IN LONG-TERM TRIALS

By M. J. JONES *and* M. SINGH

International Center for Agricultural Research in the Dry Areas (ICARDA), PO Box 5466, Aleppo, Syria

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SUMMARY

Trends over time in annual crop yields potentially provide measures of the likely long-term sustainability of cropping systems. However, where large annual variability in the growth environment is responsible for most of the large year-to-year yield differences, appropriate analytical techniques must be developed to distinguish real long-term trends from the 'background noise'. This paper presents models for the estimation of time trends in the yield data from crop rotation systems and discusses the results of applying these models to yield values from two types of long-term trial involving barley, each conducted at two sites in northern Syria.

The models used were linear with respect to time (years) and allowed for seasonal effects by means of a quadratic relationship on total rainfall and a linear relationship on planting date. A more complex model might account for more of the variance, but restrictions were imposed by the limited number of degrees of freedom (number of years of data less one) and the choice of meaningful single-valued parameters of growth-season conditions. For many experimental treatments the model accounted for less of the total variance at the wetter site. This may be due to seasonal bufferring by soil moisture stored at depth from one year to the next, and future iterations of the analysis will try to allow for this. The appropriateness of the linear time function is also questioned, and alternative functions will be tested along with alternative structures for plot errors over time.

INTRODUCTION

This paper is based on the thesis that time trends in productivity, if they can be estimated reliably, provide strong indicators of the likely long-term sustainability of a crop production system. Further, comparison of the trends measured for different systems in the same trial may be expected to show which systems are 'safer' and perhaps also suggest which specific factors (for example, input rates, husbandry practices) are responsible for any differences. Crop sequence may be one major factor in long-term yields trends; continuous cropping (same crop grown every year) is widely regarded as a high-risk system, unlikely to be sustainable because of the probable build-up of adverse biotic factors; in contrast, sequences (or 'rotations') of two or more different crops are usually considered more likely to be sustainable, particularly if they include a legume. In both cases, actual long-term system performance may also depend heavily on input use and management decisions; for example, appropriate use of fertilizer may stave off yield decline almost indefinitely in otherwise unsustainable low-fertility systems.

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Estimation of the changes over time in crop yields from various cropping systems at Rothamsted, UK, has been discussed by Dyke (1988), Jenkinson *et al.* (1994) and Barnet *et al.* (1994), and those of some experiments at Iowa Experimental Station by Fuller and Cady (1965). However, in more marginal production situations, reliable identification of productivity trends may be difficult. Background noise from natural annual variability in the biophysical environment – particularly in dry environments, that of rainfall – tends to obscure all but the most extreme yield trends and inter-system trend differences. Statistical techniques have recently been developed in ICARDA to try to overcome this difficulty (Singh and Jones, 1997a; b), and the work presented here describes the application of these new techniques to data coming from a number of long-term 'barley-system' trials in northern Syria.

In the simplest terms, the statistical challenge is to model crop yield in terms of time (years) and those environmental parameters whose annual variability contributes most to the 'noise'. These parameters (or variables) include, potentially, not only rainfall but temperature values, and such management factors as sowing date. Information on these variables is usually available, but others (for example, the time and severity of pest and disease attack) are not always well recorded and some may not even have been noticed. Even where good information exists, hard decisions have to be made about how best to summarize it into single values for use in simple multiple-regression models. In the case of rainfall, we use total annual (or cropping season) amount but, undoubtedly, that single value cannot capture all the effects of the season's rainfall (including its temporal distribution) on crop performance.

A major limitation is the number of statistical degrees of freedom, which is determined by the number of years of data less one. Even with a moderate-length time series of plot yield values (say, 15 years), it is difficult to accommodate many variables in the regression equation and still leave a reasonable number of error degrees of freedom by which to assess significance. Part of the challenge, therefore, is to select that subset of variables that best describes the annual environmental effect on crop yield. Another question concerns the choice of time function (linear, cubic or exponential). So far, only linear functions have been used, but many natural systems eventually find an equilibrium level; it may be that some production systems with a negative yield trend now may eventually stabilize at a lower production level that could then be described as biologically 'sustainable'.

Further, the nature of the error term also plays a key role in the estimation of the parameters of the model (including time trends) and testing their significance. In contrast to the case of annual trials conducted on different sites each year, in long-term trials measurements made on the same plots each year cannot be regarded as independent of each other. Suitable error covariance structures are needed to account for the dependencies and heterogeneity of variances of the plot-level 'errors' arising over time. Moreover, the algebraic complexity of the analysis differs according to whether the data come from the same plots each year (as is the

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case in continuous cropping) or from the same plots only every alternate year (as in a simple two-year rotation).

Singh and Jones (1997a) give a procedure for estimating time trends in data from a trial growing continuous barley which incorporated a first-order auto-correlation structure in the errors, and this procedure has been extended to crops grown in a two-course rotation (Singh and Jones, 1997b). Here these procedures have been applied to grain and straw yields of barley (a) in four two-course rotations at two fertility levels, and (b) in continuously cropped barley under nine fertility regimes – both cropping systems conducted at two sites in northern Syria. Both trials pertain to rainfed, barley-based cropping systems that predominate in the driest arable areas of West Asia and North Africa (Jones *et al*., 1993). The first was established to compare the productivity of barley in different rotations and that of the rotations themselves, each under different fertilizer regimes. The second was to test the effectiveness of fertilizer in averting yield decline in continuously cropped barley.

MATERIALS AND METHODS

Field operations

Two-course rotation trials. Similar trials were established at two (ICARDA) experimental stations in northern Syria (Tel Hadya and Breda) in the 1982–83 cropping season, each comprising a number of two-year barley-based rotations combined in an incomplete factorial design with several fertilization regimes. Full details are given in Jones and Singh (1995). In the present paper for each of these trials the performance of barley (*Hordeum vulgare*) was evaluated in four of the rotations, each under two fertilizer regimes. The rotations were as follows:

B–P, L: barley–peas or lathyrus (peas (*Pisum sativum*) grown from 1982–83 to 1985–86 replaced by lathyrus (*Lathyrus sativus*) from 1986–87 onwards);
B–V: barley–vetch (*Vicia sativa*);
B–F: barley–fallow (clean);
B–B: barley–barley (continuous cropping).

The two fertilizer regimes were:

F+: $N:P_2O_5$ (20:60 kg ha^{-1}) applied every two years to the barley phase;
F−: No fertilizer.

The B–B plots in the F+ regime were two halves of the B–B rotations in which only the fertilizer regime rotated biennially.

All the rotation and fertility treatments were arranged in randomized complete blocks, with three replications. The present study is based on observed grain and straw yields (kg ha^{-1}), planting dates (days after 31 October) and cropping season rainfall totals (mm), over the period of 12 years (six rotations) from 1983–84 to 1994–95.

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Continuous barley trials. Another pair of similar trials was set up at Tel Hadya and Breda in 1986–87, each involving two contrasting cropping systems: continuous annual barley under the nine factorial combinations of three annual rates of nitrogen (0, 60 and 120 kg N ha^{-1}) and three annual rates of phosphorus (0, 45 and 90 kg P_2O_5 ha^{-1}), and barley–fallow rotations under two of the same fertilizer regimes (0:0 and 120:90, applied biennially). At each site there were six replicates of each treatment combination under complete randomization. Data were examined from the continuous barley treatments only, for grain and straw yields, planting date and seasonal rainfall totals, for the nine-year period, 1986–87 to 1994–95. The annual values of rainfall and planting date, along with the soil parameters are given in Table 1.

Model and estimation of time trends

Continuous cropping. Let Y_t ($t = 1, 2, \ldots n$) be the observations over n annual time points on the same plot under a given annual fertilizer treatment. The yields from these plots may be modelled as a linear, or non-linear function in time (Singh and Jones, 1997a). We shall consider the case of multiple regression (such as linear, quadratic on rainfall, linear on date of planting and linear on time). The time trends, response to rainfall and plot-error structure and its parameters could be plot specific (Barnett, 1994), or they might each vary only with fertility treatments

Table 1. Site and soil data and rainfall and planting times for the experimental locations.

	Tel Hadya							Breda				
	Site and soil data											
Location	lat 36°01′N, long 35°56′E							lat 35°56′N, long 37°10′E				
Altitude (m)	284							300				
Mean annual rainfall (mm)	332							262				
Soil classification												
USDA system	Chromoxerertic Rhodoxeralf							Typic Calciorthid				
FAO system	Vertic (Calcic) Luvisol							Calcic Xerosol				
Soil properties (0–20 cm)†												
Texture	Clay							Clay loam				
Clay (%)	55.0							29.0				
$CaCO_3$ (%)	29.0							26.0				
pH (1:1 water)	8.0							8.3				
Organic C (%)	0.29							0.47				
Available P (Olsen) (ppm)	4.0							3.0				
	Rainfall and date of planting											
Year	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Rainfall (mm) at Breda	196	245	191	222	330	127	153	205	213	240	282	208
Planting‡	15	10	61	26	17	16	8	20	14	28	17	26
Rainfall (mm) at Tel Hadya	221	330	267	306	384	188	196	238	239	241	328	279
Planting	15	15	69	12	30	14	6	27	19	22	36	37

† Data from Harmsen (1984); ‡ planting in days after 31 October in the previous year.

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for a given crop rotation. Considering a general formulation for p explanatory variables $X_1, X_2, \ldots X_p$, model for Y_t would then be model (a):

$$Y_t = \alpha + \beta_1 X_{1t} + \beta_2 X_{2t} + \ldots + \beta_p X_{pt} + ct + \varepsilon_t \tag{1}$$

where integer valued $t = 1, 2, \ldots n$. In Equation 1, α is the intercept, βs are regression coefficients associated with Xs and c is the time trend measure of annual increase or decrease in yield. The quantities ε_ts are errors arising at time t on the same plot and are assumed to follow a normal distribution with mean 0 and constant variance σ_ε^2 . One way to account for the dependence in the errors arising over time from the same plot is to consider an autocorrelation structure among the time series of the errors. We have considered first-order autocorrelation in the errors as in the following:

$$\varepsilon_t = \phi\varepsilon_{t-1} + \eta_t \quad \text{and} \quad t = 2, 3, \ldots n \tag{2}$$

where η_t are assumed independent normal variables with mean zero and variance $\sigma_\varepsilon^2 = \sigma_\eta^2/(1 - \phi^2)$.

Two-course crop rotations. Experiments were considered where both phases of the two-course rotations were present every year. For convenience, the two courses were denoted by B (for barley) and V (for vetch). Under a given fertility treatment, there were two plots each year in a replicate block, one under B and the other under V. These two plots received crops V and B, respectively, in the second year, and so on.

Let the yields of barley and rainfall in the t-th year be Y_t and R_t respectively. M cycles give $n = 2M$ years. Thus, on B-plot there is a series of yields: $Y_1, Y_3, \ldots Y_{2m-1}$ and on V-plot a series of yields: $Y_2, Y_4, \ldots Y_{2m}$ for $m = 1, 2, \ldots M$.

In this case also, the parameters of a model (including the variance component of associated errors) could vary with plot (and could be applied on longer series) or could vary with the treatment applied and be constant for all the plots under the same treatment (and could be applied on shorter series).

Denoting the intercept by α_1 for B-plot and α_2 for V-plot, the series of yields Y_t ($t = 2m - 1$ for B-plot and $t = 2m$ for V-plot; $m = 1, 2, \ldots M$) in terms of regressors $X_1, X_2, \ldots X_p$ and time t are modelled by model (b):

$$\text{(for B-plot)} \qquad Y_t = \alpha_1 + \beta_1 X_{1t} + \beta_2 X_{2t} + \ldots + \beta_p X_{pt} + cm + \varepsilon_{1t} \tag{3}$$

$$(t = 2m - 1;\ m = 1, 2, \ldots M);\ \text{and}$$

$$\text{(for V-plot)} \qquad Y_t = \alpha_2 + \beta_1 X_{1t} + \beta_2 X_{2t} + \ldots + \beta_p X_{pt} + cm + \varepsilon_{2t} \tag{4}$$

$$(t = 2m;\ m = 1, 2, \ldots M),$$

where βs are regression coefficients associated with Xs and c is the time trend parameter measuring increase or decrease per cycle of rotation. The quantities ε_{1t} and ε_{2t} are independent (since they arise from different plots), and are assumed to

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follow normal distribution with mean zero and common variance σ_ε^2 and to possess the autocorrelation structures

$$\varepsilon_{1t} = \phi\varepsilon_{1t-2} + \eta_{1t} \quad (t = 2m - 1)$$

and

$$\varepsilon_{2t} = \phi\varepsilon_{2t-2} + \eta_{2t} \quad (t = 2m)$$

ϕ is the common autocorrelation between the errors arising from the same plot. The random variables η_{1t}s and η_{2t}s are independently and normally distributed with mean zero and variance σ_η^2.

In a rather longer series, parameters of the model may adapt to the specific plot conditions, that is, may vary with the plot, in which case it may be worthwhile to estimate them for each plot. The plot-wise estimates of the parameters can then be analysed according to the experimental design used in order to evaluate the rotation or fertility treatments for the time trends. Results using these were obtained from the continuous barley trials with nine fertility regimes under continuous cropping.

Minimum number of years or rotation cycles required to detect significant time-trends. The minimum number of years n or cycles M can be obtained using the estimate $\hat{c}$ for time trend c, expression for its variance and level of significance to detect significant time trends. Thus, c would be detected significant at 100 α% level if

$$|\hat{c}|/(\hat{\text{var}}\ (\hat{c}))^{1/2} \geqslant t_{v,\alpha/2} \tag{5}$$

where $t_{v',\alpha/2}$ is upper $\alpha/2$ probability point of t-distribution with v d.f. and v is the degree of freedom on which the estimate of variance components, such as σ_ε^2, σ_η^2, used in the estimate $\hat{\text{var}}(\hat{c})$, are based. These are given for each model in Table 2.

RESULTS

The yield values were modelled using

$$Y_t = \alpha + \beta_1 R_t + \beta_2 R_t^2 + \beta_3 D_t + ct\ (\text{or } m) + \varepsilon_t$$

as discussed in Equations 1, 2, 3 and 4. The quantities R_t and D_t represent rainfall (mm) and date of planting (days after 31 October) in the previous year $(t - 1)$ and m is the corresponding cycle number.

Rotation trials

Numerical values of the estimated time trends and the number of cycles required to detect significant time trends for grain and straw yields are given in Table 3; the broad pattern of the direction of those trends is summarized in Table 4. From this, it can be seen that:

- the two rotations with legumes (B–P, L and B–V) behaved fairly similarly.

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Table 2. Expressions for variance of the estimates of the time trend and equations to determine the minimum number of years or cycles to detect significant time trends†.

Variances of time trend estimates $(\mathrm{var}(\hat{c}))$
Model (a) $12\sigma_\eta^2/\{rn(n-1)(n-2)(1-\rho_{\mathrm{m}}^{*2})(1-\phi)^2\}$
Model (b) $12\sigma_\eta^2/\{rM(M-1)(M-2)(1-\rho_{\mathrm{m}}^{*2})(1-\phi)^2\}$
Minimum number of years (n) or cycles (M) for detecting significant time trend
Model (a) $n(n-1)(n-2) \geqslant 12t_{v,\alpha/2}^2\hat{\sigma}_\eta^2/\{r\hat{c}^2(1-\hat{\rho}_{\mathrm{m}}^{*2})(1-\hat{\phi})^2\} = Q_1$, say.
An approximate solution is $n = Q_1^{1/3}$
Model (b) $M(M-1)(M-2) \geqslant 6t_{v,\alpha/2}^2\hat{\sigma}_\eta^2/\{r\hat{c}^2(1-\hat{\rho}_{\mathrm{m}}^{*2})(1-\hat{\phi})^2\} = Q_2$, say.
An approximate solution is $M = Q_2^{1/3}$

† n, M = number of years and cycles of rotations respectively; r = number of replications; $\hat{c}$ = the time trend estimate; $\mathrm{var}(\hat{c})$ = variance of $\hat{c}$; ρ_{m}^{*2} = coefficient of determination of transformed time $t^* = t - \phi(t-1)$ on the other transformed explanatory variables $X_{it}^* = X_{it} - \phi X_{it-1}$ $(i = 1, 2, \ldots p)$; p = number of explanatory variables; $\hat{\rho}_{\mathrm{m}}^{*2}$ an estimate of ρ_{m}^{*2}; ϕ, $\hat{\phi}$ = first order autocorrelation between the errors arising over time in the same plot, its estimate; σ_η^2, $\hat{\sigma}_\eta^2$ = variance, the estimate of the variance of independently and normally distributed random variables η_ts defined in the autocorrelation errors structures (Model a and Model b).

Yield trends were positive where fertilizer was used, except for grain at Breda where (surprisingly) it was only the unfertilized plots that showed a positive (or level) trend;

- fallow (in B–F) gave generally increasing yield trends at Breda but only for grain yield in fertilized plots at Tel Hadya; and
- continuous barley cultivation (B–B) produced negative (or level) trends in all cases except that of straw at Breda (with and without fertilizer).

Two outstanding features of these results were (1) the generally positive trend of straw yields at Breda and (2) the generally negative trend of straw and grain yields at Tel Hadya in the absence of fertilizer. A third outstanding feature was the clear difference between Breda and Tel Hadya in the amounts of the variance accounted for ($100\bar{\mathrm{R}}^2$ values). Applied to the Breda data, the model accounted for 58–85% and 61–81% of the grain yield variance and straw yield variance, respectively, but almost all Tel Hadya values were much lower, indicating a poorer fit of the model to the data. It appears that at Tel Hadya there was at least one more seasonal factor, in addition to rainfall, planting date and time trend, that was seriously influencing barley yields. The poorest fit of the model occurred with the B–F data. This may possibly reflect the model's failure to take into account the storage over the summer period of moisture accumulated in the profile during the previous season's clean fallow. Harris (1995) reported values of fallow efficiency (proportion of rainfall in one season stored through the summer to benefit the following crop) at Tel Hadya of 10–40%. Forage legume crops may

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Table 3. Mean yields, estimates of time trends and time (number of two-year cycles rounded to the next integer) required to detect significant time trends in grain and straw yields (plot errors follow first-order autocorrelation structure).

Site	Rotation	Fertilizer regime†	Mean yield (t ha^{-1})	Time trend‡ (kg ha^{-1} a^{-1})	Pr§	$\hat{\phi}$	$\%\bar{R}^2$	Cycle
				Grain yield				
Breda	B–P, L	F−	1.06	−2.2 (57.27)	0.971	0.111	73	71
	B–P, L	F+	1.66	−51.7 (51.18)	0.323	−0.246	85	9
	B–V	F−	1.08	21.9 (59.93)	0.718	0.143	70	17
	B–V	F+	1.63	−55.0 (64.35)	0.402	−0.251	75	10
	B–F	F−	1.34	61.5 (74.9)	0.420	0.279	72	11
	B–F	F+	1.97	119.9 (73.25)	0.115	−0.021	67	7
	B–B	F−	0.73	−57.1 (23.11)	0.020	−0.198	63	4
	B–B	F+	1.26	−32.7 (50.4)	0.522	−0.132	58	12
Tel Hadya	B–P, L	F−	1.88	−46.5 (73.24)	0.532	−0.002	6	12
	B–P, L	F+	2.50	58.1 (62.98)	0.366	−0.279	26	10
	B–V	F−	1.85	−125.6 (42.2)	0.007	−0.039	48	5
	B–V	F+	2.43	129.5 (73.7)	0.092	−0.248	16	7
	B–F	F−	2.25	−113.8 (76.04)	0.148	−0.052	-ve	8
	B–F	F+	2.93	55.0 (87.5)	0.535	−0.199	-ve	12
	B–B	F−	1.11	−143.1 (43.80)	0.003	0.032	41	4
	B–B	F+	2.01	−29.1 (66.7)	0.667	−0.300	18	15
				Straw yield				
Breda	B–P, L	F−	1.64	107.8 (59.55)	0.083	−0.208	72	7
	B–P, L	F+	2.97	150.4 (76.20)	0.060	−0.356	81	7
	B–V	F−	1.69	136.6 (65.42)	0.048	−0.083	70	6
	B–V	F+	2.92	122.3 (86.5)	0.170	−0.241	77	8
	B–F	F−	1.89	139.8 (86.5)	0.119	−0.052	68	7
	B–F	F+	3.14	220.9 (67.01)	0.003	−0.338	80	5
	B–B	F−	1.27	74.1 (24.29)	0.005	−0.359	61	4
	B–B	F+	2.34	135.2 (65.65)	0.050	−0.209	65	6
Tel Hadya	B–P, L	F−	2.41	−122.8 (106.6)	0.261	0.209	25	7
	B–P, L	F+	4.01	96.6 (88.80)	0.287	−0.167	53	9
	B–V	F−	2.40	−139.7 (34.02)	0.001	−0.173	66	5
	B–V	F+	3.80	147.7 (89.85)	0.113	−0.309	38	7
	B–F	F−	2.88	−250 (134.6)	0.075	0.317	14	7
	B–F	F+	4.59	−54.9 (118.1)	0.647	−0.207	16	15
	B–B	F−	1.46	−50.1 (38.82)	0.207	−0.057	35	6
	B–B	F+	2.99	2.6 (72.21)	0.972	−0.239	46	75

† F− and F+ = unfertilized and fertilized regimes respectively; ‡ standard errors in parentheses;
§ Pr = probability of F – distributed random variable exceeding the observed variance ratio for time trend under the null hypothesis of no time trend; $\hat{\phi}$ = estimate of the first-order autocorrelation parameter ϕ; $\%\bar{R}^2$ ($= 100\bar{R}^2$) = percentage variance accounted for.

also leave some water in the soil after a high-rainfall season. However, at Breda, such effects, even after fallow, were at most very small.

Estimates of the number of years needed to detect significant time trends might be assumed to provide a measure of the time scale required to establish the reality of 'production sustainability' in trials of this nature. Apart from two outliers (Breda unfertilized B–P, L grain; Tel Hadya fertilized B–B straw), the number of

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Table 4. Broad pattern of yield trends in the two-course rotation trials at Breda and Tel Hadya†.

Location	Yield	Fertilizer regime	Rotation			
			B–P, L	B–V	B–F	B–B
Breda	Grain	F−	(−)	+	+	−*
		F+	−	−	++	−
	Straw	F−	+s	+*	+	+**
		F+	+s	+	++**	+*
Tel Hadya	Grain	F−	−	−*	−	−
		F+	+	++s	+	−
	Straw	F−	−	−**	−s	−
		F+	+	+	−	(+)

† F− and F+ = unfertilized and fertilized regimes respectively; +, − = signs of the time trend estimates; ( ) = very small time trend estimates (for which the sign seemed unimportant); ++ = grain yield trends exceeding 100 kg ha^{-1} a^{-1} and straw yield trend exceeding 200 kg ha^{-1} a^{-1}; s, * and ** = statistically significant at $p < 0.1$, 0.05 and 0.01 respectively.

cycles required by most treatments lay between 4 and 10, which is 8–20 years. However, the stronger the trend numerically, the shorter the period required to establish significance. Thus, the two outliers mentioned showed almost negligible trends, indicating that within the limits of the trial and the statistical analysis these treatments demonstrated yield stability. If, however, such stability represents sustainability it will, apparently, take around 70 cycles or 140 years to establish that it is significant. In contrast, the significance of the stronger trends can be established much more quickly. In the case of significant negative trends it appears reasonable to conclude that such treatments will not provide production sustainability at current yield levels – they will either decline to zero or stabilize at a lower level. Where the observed trend so far has been positive, productivity clearly cannot continue to rise indefinitely, and some yield maximum or gradually achieved plateau must be anticipated. The need to determine the most appropriate time function to use, as noted earlier in the paper, is evident.

Continuous cropping trials

Time trend coefficients and the number of years needed to detect significant trends are given in Table 5. At Breda, trends come out as generally negative for grain, irrespective of fertilizer treatment, and also for straw in the absence of applied nitrogen. At Tel Hadya, grain and straw trends were all positive except where nitrogen was applied in the absence of phosphate fertilizer. The lowest time requirement to detect significant trends was 10–18 years for grain yield decline at Breda. For straw at Breda, and for both grain and straw in most Tel Hadya treatments, the period is considerably longer (20–50 years).

DISCUSSION

The purpose of the present paper is to demonstrate and discuss a method to

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Table 5. Estimates of time trends (kg ha^{-1} a^{-1}), mean yields (t ha^{-1} in parentheses) and years to detect significant time trends under the nine fertilizer regimes for grain and straw yields (based on nine years of data, 1986–87 to 1994–95) at Breda and Tel Hadya.

	Grain			Straw		
P_2O_5 (kg ha^{-1})	0	45	90	0	45	90
Nitrogen (kg N ha^{-1})						
			Breda			
0	−119	−81	−101	−35	−14	−6
	(1.31)	(1.44)	(1.38)	(1.63)	(1.71)	(1.82)
60	−26	−125	−65	53	72	107
	(1.21)	(1.80)	(1.96)	(1.62)	(2.76)	(3.02)
120	−23	−95	−102	89	83	92
	(1.10)	(1.70)	(1.78)	(1.60)	(2.68)	(3.27)
s.e.		21.9			26.5	
			Tel Hadya			
0	29	33	82	92	50	134
	(1.44)	(1.57)	(1.53)	(1.59)	(1.78)	(1.78)
60	−55	152	142	−105	149	100
	(1.96)	(2.41)	(2.56)	(2.47)	(3.41)	(3.72)
120	−80	108	184	−71	126	97
	(1.98)	(2.33)	(2.37)	(2.65)	(3.71)	(4.04)
s.e.		27.9			62.5	
			Years to detect time trends at Breda			
0	10	15	14	24	39	39
60	18	12	15	35	36	46
120	17	15	14	30	24	31
			Years to detect time trends at Tel Hadya			
0	40	47	40	33	32	19
60	50	19	39	21	14	28
120	30	23	15	24	28	25

identify yield time trends, eliminating as far as possible the effect of annual variability. Results based even on relatively short data sets were sufficiently promising to justify further effort. They are discussed here in terms of their apparent agronomic implications, and the needs and opportunities identified for future improvement of the statistical method.

The strongest agronomic information was available for the continuous barley system (B–B), which was represented in both trials. At Breda, both trials indicated grain yield decline that cannot be prevented even by the use of fertilizer. At the same time, straw yields appeared to increase, although the continuous barley trials showed that nitrogen fertilizer was needed for this. However, results from Tel Hadya were more contradictory. The two-course barley-based rotations showed predominantly negative trends, but for the continuous barley trials both grain and straw yields apparently increased in the absence of fertilizer, or with nitrogen additions provided phosphate was also applied.

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Of the other two-year barley-based rotations, that with fallow (B–F) showed positive grain and straw trends at Breda but not at Tel Hadya (where the analysis accounted for little of the variance). Rotations with forage legumes (B–P, L and B–V) showed increasing time trends for straw yields at Breda and, with fertilization, for grain and straw yields at Tel Hadya.

It is necessary to treat all these findings sceptically. With the possible exception of those for grain yield at Breda, all trends should be regarded as provisional, particularly those that are counter-intuitive. Despite the poorer fit of the model at Tel Hadya, some results there (positive and negative trends matching the use and non-use of fertilizer) were closer to expectation than those from Breda. Estimates of the time required to establish trend significance suggested that both trials needed to be continued for longer. While this was almost certainly true, more rapid advances may be made through improvements to the model. Two possible improvements arose from the present analysis:

(i) an improved time function to account for curvilinearity;
(ii) a more appropriate choice of variables to account for annual differences.

As observed above, with regard to (ii) residual soil moisture (that is, deep-stored profile moisture present at sowing time) may be an important annually variable factor at Tel Hadya, particularly in the barley–fallow rotation. No soil moisture data were available from this trial, but the previous year's rainfall total may be an adequate proxy – generally, the greater the rainfall, the deeper its penetration, and the greater the deep storage from one season to the next. This variable needs to be tested in the model for Tel Hadya.

Other environmental parameters such as temperature, humidity, sunshine hours have been suggested for inclusion in the time-trend equations to improve their ability to account for annual variability. These data were available but difficult to use. Not only was it difficult, for instance, to summarize a season's temperature characteristics into a meaningful single value, but some parameters were meaningless except in the context of others – thus, plentiful sunshine hours had a positive effect only if rainfall was adequate. In addition, each extra single-value parameter (or interaction variable between parameters) required an extra degree of freedom, essentially one more year of data. There was a strong incentive here to keep the model simple.

A pessimistic view might be that, although variables such as a rainfall and temperature may describe the environment physically, even a reasonably complex function of them may not provide an adequate biological measure of the environment experienced by the crop. A possible alternative is to follow the practice used in crop improvement programmes in the evaluation of genotype × environment interactions. Mean yield of all genotypes in a particular site–year situation is assumed to integrate all the components of that growth environment and so is considered as a reasonable biological measure for it, provided the set of genotypes is reasonably representative (Yates and Cochran, 1938; Finlay and Wilkinson, 1963; Eberhart and Russell, 1966). The same

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approach could be applied to the long-term trial analysis, in this case using the mean across trial treatments or, probably better, the mean across routine research-station production fields as an index of the biological favourability of the growing season.

Besides a number of forms of the time trends (other than linear as in the present context) one may also evaluate the effect of covariance error matrices (Singh *et al*., 1997) on the time trend estimates, and of the outliers in the data. If the series were long enough, it might be worth estimating the yield response function specific to the particular plots and then combine the estimates of time trend and of the number of cycles needed to detect significant time trend for a given fertility and crop rotation.

CONCLUSIONS

The major determinant of barley yield each year at Tel Hadya and Breda was rainfall. The closeness of this dependence is illustrated by Fig. 1, which also makes clear the extent to which any underlying time trend of yield was unavoidably obscured by the large random variation of the rainfall. The same yield values are presented in Fig. 2, as linear regressions on time, after allowance for the linear and quadratic effects of rainfall and the linear effect of planting date.This is a great improvement, although, as yet, the standard errors of the regression slopes are inconveniently large (Table 3); it is unlikely that the slopes of any two regressions could be shown to be significantly different from each other and this was not attempted. However, once further refinement of the method has led to lower standard errors, such comparisons will provide a valuable test, showing whether any two treatments have differed significantly in their effect on long-term yield trends. (A statistically more complex test will be required if a different time function is used, but the principle of treatment comparison is not different.)

As the high standard errors show, the time sequences of data so far available are, even at best, barely long enough to reveal significant trends. All the indications are that perhaps 20–25 years would be needed before statistically significant trends could be identified for a majority of treatments. This is too long for most purposes. As the discussion above has indicated, any refinement of method would involve an improved set of variables in the regression equation; and possibilities for barley in northern Syria include residual soil moisture (or the previous year's rainfall total), 'site mean yield' (as in genotype × environment analyses) and a different time function.

Further, an appropriate form of the time-trends in the light of an appropriately selected variance–covariance structure for the plot errors should be considered for estimation of the time trend with parameters of the model varying with the plot or the treatments (for example, fertility and cropping system).

Such testing of *ad hoc*, situation-specific parameters will probably be a necessary procedure wherever this method is applied. However, experience with the present trials suggests some rules for experimental design and data collection that may

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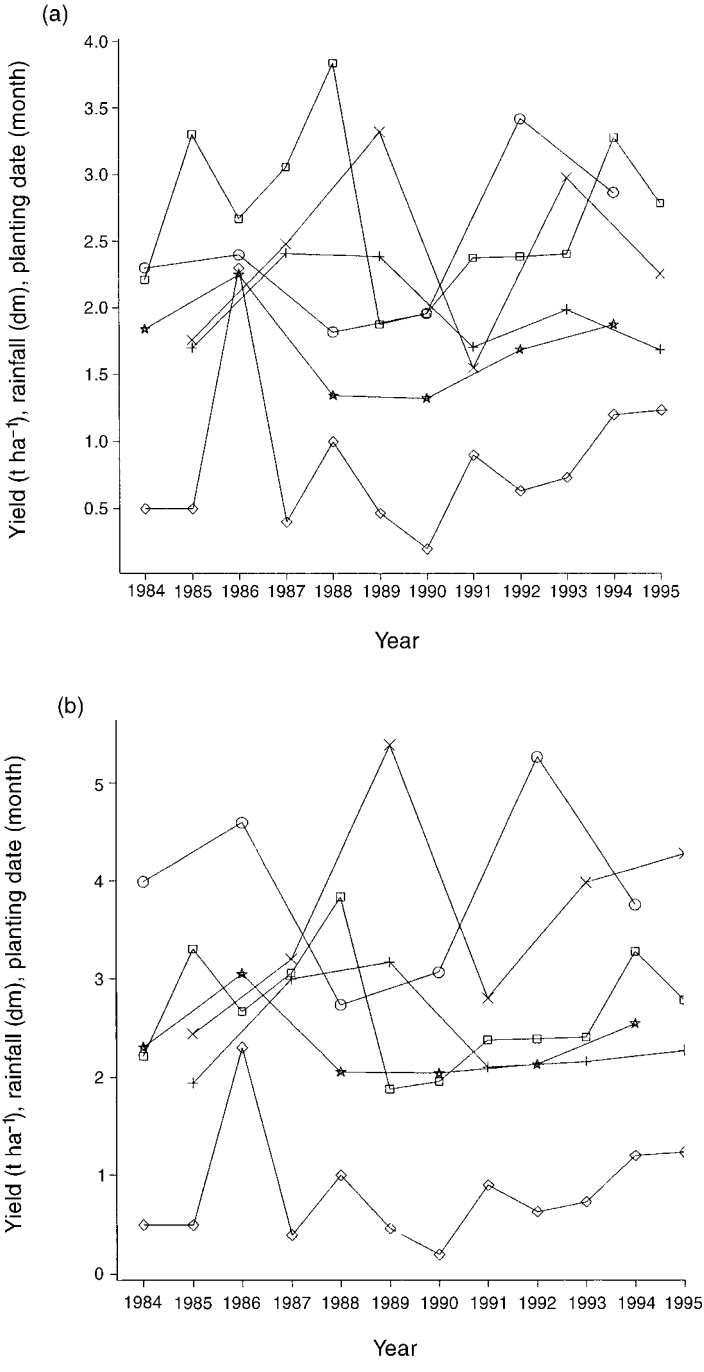


Fig. 1 Time series of barley mean yields in barley–vetch (*Vicia sativa*) rotation under fertilized (rotation plots in barley beginning 1985, ×—× and 1984, ○—○) and unfertilized (rotation plots in barley beginning 1985, +—+ and 1984, ✳—✳) regimes at Tel Hadya for (a) grain and (b) straw, rainfall (dm, □—□) and planting date (month, ◇—◇) after 31 October in the previous year.

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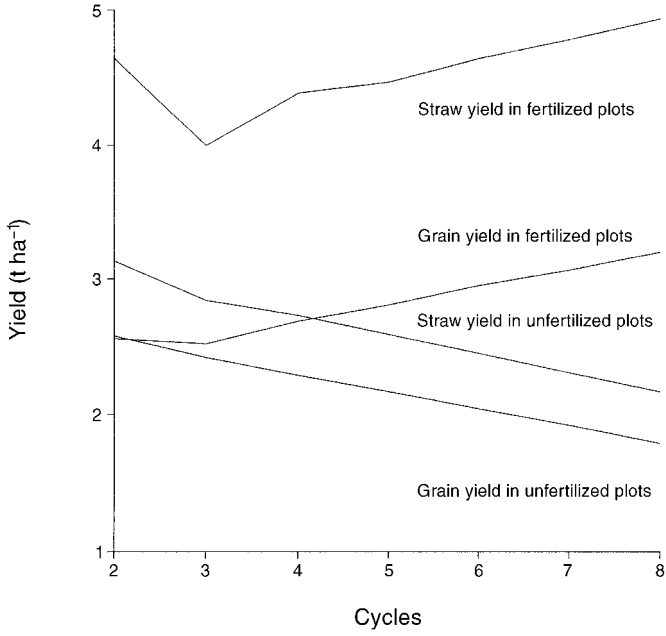


Fig. 2. Predicted barley grain and straw yields in barley–vetch (*Vicia sativa*) rotation under fertilized and unfertilized regimes at Tel Hadya (with a long-term average rainfall of 332 mm and planting date 15 November).

serve to keep experimental errors to a minimum. Most important is a suitable field design. This generally involves the choice of an effective blocking system leading to homogeneous plots within each block. In the present work, the design of the continuous barley trials was not ideal. Originally planned to accommodate a factorial combination of two additional treatments that were never implemented, the resulting layout became a completely randomized design of six replicates. The two-year barley-based rotations comprised (at each site) three replicates of both annual phases of 21 treatments – a large trial. For present purposes, more replicates of a smaller number of treatments, in a well-blocked design, would have increased precision, though at the expense of a reduced number of agronomic systems. However, these old trials were not planned to demonstrate long-term yield trends but to compare many agronomic management combinations. For new trials, it will be important to prioritize aims before settling the design. Further, if one aim is to detect yield trends, prior identification of appropriate parameters for defining the quality of growth seasons and a system for recording them is essential. Considerable experience of the crops and cropping systems is an important precondition for this.

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