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Bioclimatology

A wheat–fallow rotation in northeastern Spain: water balance–yield considerations

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Summary — A 35-yr time series of dryland wheat yields and corresponding monthly rainfall data from the Los Monegros/La Ribera del Ebro–Zaragoza area in Central Aragon have been examined with a view to determining the efficacy of the wheat–fallow rotation. Grain yields are low (average of 1 050 kg/ha) and highly dependent on seasonal (October–May) rainfall. In some years no harvestable yield is possible. The contribution of stored water during the fallow period appears minor either because of a low soil water-holding capacity, poor weed control, or because of the nature of the rainfall distribution. The latter is characterised by the absence of any well-defined rainy season and in any month there exists a strong probability of having either no or an extremely low amount of rain (< 10 mm). The Tanner and Sinclair (1983) result suggesting that transpiration efficiency is a stable characteristic for a cropping system is used to calculate transpiration from grain yields. Evaporative losses are then calculated by difference with the seasonal rainfall on the assumption that drainage and surface runoff were negligible. On average, 70% of the average seasonal rainfall is estimated to be lost either as evaporation or transpiration by weeds. The water use efficiency of grain production approached the average potential (16.7 kg•ha^{-1} per mm water transpired) in only 3 out of 35 yr. In other years, evaporative losses accounted for a greater proportion of evapotranspiration, reflecting reductions in growth due to factors other than water such as poor plant nutrition, pests and diseases, etc.

dryland wheat / water budget / semi-arid region / fallow period / dry matter production / grain yield / water-use efficiency

Résumé — Un système de culture blé-jachère au nord-est de l'Espagne : efficience de jachère et relation bilan hydrique-rendement. *Dans le but de déterminer l'efficacité d'une rotation blé-jachère, on analyse une série de 35 ans de données de production de blé et les pluviométries mensuelles correspondantes sur les zones de Los Monegros et de La Ribera del Ebro-Zaragoza, dans le centre de l'Aragon (Espagne). Les rendements en grains sont faibles (1 050 kg/ha en moyenne) et dépendent fortement des précipitations saisonnières (octobre-mai). La contribution de l'eau stockée pendant la période de jachère apparaît peu importante, en raison soit de la faible réserve utile du sol, soit du contrôle insuffisant des mauvaises herbes, soit de la distribution des pluies. Celle-ci se caractérise par l'absence d'une saison pluvieuse bien définie et par une forte probabilité de précipitations mensuelles non efficaces (< 10 mm). La conclusion de Tanner et Sinclair (1983), selon laquelle l'efficacité de la transpiration est une caractéristique stable d'un système de culture donnée, est utilisée ici pour évaluer la transpiration à partir des rendements en grain. Les pertes par évaporation sont ensuite estimées par différence avec la précipitation saisonnière, sous l'hypothèse d'un drainage et d'un ruissellement superficiel négligeables. En moyenne, 70% des précipitations sont considérées comme perdues par évaporation ou transpiration par les mauvaises herbes. L'efficience de l'utilisation de l'eau pour la production de grains ne s'est approchée du potentiel moyen (16,7 kg.ha^{-1} par mm de l'eau transpirée) que dans 3 années sur les 35 étudiées. Pour les autres années, les pertes par évaporation supérieures indiquent sans doute que les réductions de croissance sont liées à d'autres facteurs que l'eau, comme le manque d'engrais, les insectes, les maladies des plantes, etc.*

blé non irrigué / bilan hydrique / semi-aride / jachère / matière sèche / rendement en grain / efficience de l'utilisation de l'eau

INTRODUCTION

Central Aragon in north-eastern Spain is one of the driest regions of the Iberian peninsula. Here 2 of the most important areas for cereal production, La Ribera del Ebro and Los Monegros (fig 1), comprise some 250 000 ha of semi-arid drylands with an average annual rainfall of < 400 mm. This low rainfall regime imposes significant constraints on agricultural production (Alberto and Machín, 1978) and is due to the mountain chains which border the Ebro River Valley, which present formidable barriers for rain-carrying storms from almost any direction. The traditional farming system is that of a cereal–fallow rotation. As in many other places, the use of the fallow period has been questioned, and in this paper we examine historical wheat yields and rainfall data in order to obtain some indications of its effectiveness in this region. A comprehensive study of fallow systems should consider, in addition to the water budget, effects on soil fertility, soil-borne diseases, weed control efficiency, flexibility of farming operations, livestock integration and costs of production. Only water balance issues will be addressed in this paper.

The inclusion of a weed-free fallow or 'resting' period is widely used in semi-arid regions to recharge soil water storage and increase the water available for the next crop. In an oft-quoted 30-yr comparison on the Great Plains, Smika (1970) found average fallow-wheat yields to be > 3 times greater than those from continuously-cropped plots. Moreover, the fallow-wheat system proved more stable with no crop failures, whereas with a continuous wheat system, no harvestable yield was obtained in > 30% of the yrs. Likewise, in the Great Konya Basin in Turkey, water stored during the fallow year was calculated to contribute between 45 and 65% of the water transpired by succeeding wheat crops (Janssen, 1972). More commonly, results are variable (French, 1978a, 1978b) and for this reason, experience obtained in other regions with differing soil and rainfall characteristics must be tempered with some local verification before advice can be given to farmers. We shall see below that one important difference between Central Aragon and some other semi-arid regions is the absence of a well-defined rainy season.

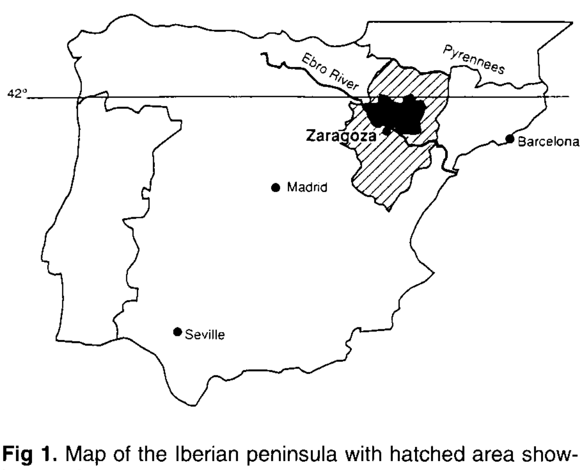

Fig 1. Map of the Iberian peninsula with hatched area showing the Aragon region and the zone in black representing the areas of La Ribera del Ebro – Zaragoza and Los Monegros.

Central to the question of water use efficiency is the balance between water transpired (*T*) by the crop and soil evaporation (*E*). The sum of these 2 water budget components is commonly referred to as evapotranspiration *(ET)*. *E* confers no or minimal physiological advantage upon the crop and thus represents a loss from the system. With an annual row crop, some soil evaporation is unavoidable and quantifying this loss under average conditions in Los Monegros is one of the aims of this study. On the other hand, many studies reviewed by de Wit (1958) and Tanner and Sinclair (1983) have shown dry-matter production (*Y*) to be proportional to *T*. Tanner and Sinclair derive the following expression for the crop yield transpiration ratio:

$$Y_T/T_T = (1/T_T) \int [kT/B\,(\overline{e^* - e})]dt \qquad [1]$$

where Y_T is total dry matter (DM) mass/area, T_T is the total transpiration/area, $(\overline{e^* - e})$ is the mean daytime difference between the saturated and actual vapour pressure, *ie* the mean daytime vapour pressure deficit, *k* is a crop specific efficiency parameter, and the integration extends over the period of active dry matter (DM) accumulation. *B* is a parameter close to unity provided leaf temperature does not depart substantially from air temperature and leaf area index exceeds 3. In practice, and despite some caveats discussed by Tanner and Sinclair, equation [1] is usually reduced to the Bierhuizen and Slatyer (1965) formulation:

$$Y_T/T_T \approx k_d/(\overline{e^* - e}) \qquad [2]$$

where k_d and $(\overline{e^* - e})$ are mean quantities over the period of growth. Because of the correlated nature of the variables of the integrand in equation [1], k_d will be smaller than *k* (Tanner and Sinclair, 1983). Monteith (1986) also shows data from the Rothamsted Experimental Station supporting the above equation. After an elegant reappraisal of previous work, Tanner and Sinclair conclude that *k* (or k_d) is a stable characteristic of a cropping system. The mean daytime vapour pressure in the denominator of equation [2] serves as an index of aridity explaining differences in transpiration efficiency attained in varying climates.

The derivation of equations [1] and [2] both depend on the ratio of the leaf intercellular CO_2 concentration (c_i) to the atmospheric concentration (c_a) remaining roughly constant over the usual conditions of crop growth. After the work of Wong *et al* (1979), c_i/c_a is often taken as 0.7 for C_3 and 0.3 for C_4 species. While this assumption has since been questioned on theoretical grounds (Farquhar and Richards, 1984), the evidence cited by Tanner and Sinclair and that of Wilson and Jamieson (1985) (reproduced here in fig 2) suggest that equation [2] provides a description that is consistent with crop behaviour in the field. Wilson and Jamieson (1985) found a value for the above-ground DM production of wheat to be of 3.1 (± 0.05) Pa independent of cultivar, sowing date and season. In view of this, we will accept equation (2] as providing a useful framework within which to consider crop production and water usage in Central Aragon.

Since $(\overline{e^* - e})$ is largely defined by local climate, Tanner and Sinclair (1983) also conclude that the 'transpiration efficiency of total biomass is a relatively unmanipulative variable'. Thus the options available for more efficient use of limited water resources by rain-fed agriculture are reduced to:

- matching the phenology of the crop to the expected water supply, and/or to periods of low varpour pressure deficit;
- management techniques, which increase the proportion of water transpired by the crop relative to that wasted by weeds or soil evaporation;
- increasing the total amount of water available.

Examples of these 3 strategies respectively include, choice of crop, cultivar and sowing dates to maximize growth when vapour pressure deficits are low, fertilization to encourage more rapid canopy development and thus in turn increase transpiration relative to soil evaporation, and lastly, fallowing and/or terracing. Breeding opportunities would seem to lie mostly in improving the harvestable proportion (harvest index) of the crop (Tanner and Sinclair, 1983) or developing shorter season varieties (Cooper *et al,* 1987).

This paper examines some aspects of the water budget in relation to crop performance within a traditional wheat–fallow rotation in the Los Monegros region. Rainfall statistics and grain yields are used to determine the importance of within-season and fallow period rainfall contributions to grain yields. As discussed by Tanner and Sinclair (1983), equation [2] gives an upper limit for water use efficiency and predictions based on this calculation will be compared those achieved in practice. This equation also provides the basis of a methodology, which, in low rainfall environments, allows *ET* to be easily decomposed into *E* and *T* components.

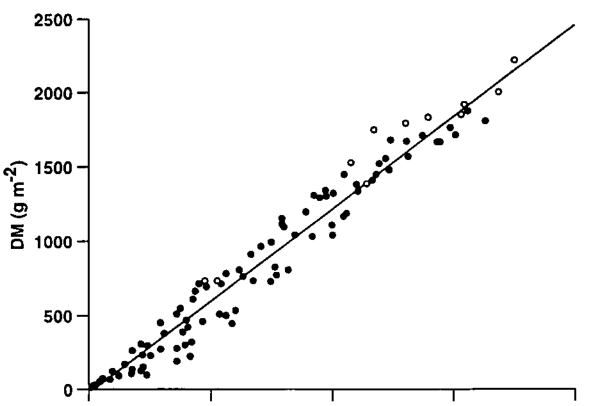

Fig 2. Relation between cumulative DM production from successive harvests and transpiration per unit vapour pressure deficit. Maximum harvests for the 11 crops (3 seasons, 2 cultivars, 2 or 3 planting dates) are represented by the open symbols. Total evapotranspiration was either measured directly using a neutron probe or calculated from a calibrated water budget. Soil evaporation was deduced using the procedure of Ritchie (1972) and Tanner and Jury (1976) (Reproduced by permission of Wilson and Jamieson (1985)).

ENVIRONMENT

Climate

Monthly rainfall statistics are listed in table I together with evaporation estimates. Monthly rainfall totals (1941 to 1989) were available from Monegrillo within a few kilometers of the site from whence yield data were obtained. The maximum daily rainfall within each month was also available. Average Priestley and Taylor (1972) monthly evaporation figures (ET_0) were calculated from hours of sunshine data tabulated by Faci and Martínez (1991). Only in December and January does the average rainfall exceed

Table I. Evapotranspiration and rainfall statistics.

Month	ET_o[a]	R (*mm*)	σ[b]	P(R < *10)*[c]	P(R *>50)* (*%*)	P(RD > *30)*[d]
Jan	17	24	22	33	12	4
Feb	37	25	23	29	12	6
March	82	26	25	29	12	2
April	115	39	38	22	27	10
May	149	51	30	8	43	32
June	168	35	27	20	18	22
July	168	22	25	47	12	12
August	148	24	20	35	18	20
Sept	118	34	37	31	31	22
Oct	60	37	37	31	18	18
Nov	43	32	35	18	16	14
Dec	18	29	26	25	21	8
Annual	1122	377	95			

[a] $ET_o = 1.26\ (s/s + \gamma)\ R_n$ where s is the slope of the saturated vapour pressure curve at the daily mean temperature, γ is the psychrometric constant, and R_n the 24-h net radiation ; [b] SD of monthly rainfall ; [c] probability of montly rainfall total < 10 mm ; [d] probability of a single day's rainfall > 30 mm.

the estimated atmospheric demand. Some indication of the chronic deficiency of water in this region is given by the disparity between the average annual rainfall (377 mm) and estimated 'potential' evaporation (1 122 mm).

Effects of drought can be accentuated by dry WNW winds *(Cierzo)* during March and April. Less frequently there are dry winds from the south at the end of May or beginning of June during grain filling. Mean daily temperatures (table II) range from 5°C in January to 26°C in July and with extreme temperatures sometimes exceeding 40°C and as low as –10°C (Biel and García de Pedraza, 1962).

Average monthly values of $(\overline{e^* - e})$ listed in table II show the expected seasonal increase in dryness. An average of 556 Pa was calculated over the period of maximum DM accumulation (January through May). Since local measurements of wet bulb temperature or humidity were not available, these values were estimated from the corresponding long-term average monthly minimum and maximum air temperatures (T_{min} and T_{max} respectively). Vapour pressure deficits were weighted towards the period of higher daytime temperatures and solar radiation loading assuming:

$$(\overline{e^* - e}) = 2/3\ (e^*(T_{max}) - e^*(T_{min}))$$

after Tanner and Sinclair (1983). This assumes that air temperature approaches the dew point at night, *ie* that the actual vapour pressure is estimated as:

$$e = e^*(T_{min})$$

This procedure can at best only describe the long-term average behaviour of daytime vapour

Table II. Mean monthly minimum and maximum temperatures and estimated vapour pressure deficits.

Month	T_{min} *(°C)*	T_{max} *(°C)*	$(\overline{e^* - e})$ *(Pa)*
Jan	3.5	9.5	272
Feb	0.5	12.5	381
March	6.7	16	628
April	9	19	692
May	11.5	21.5	805
June	15.8	26.5	
July	17.5	29.5	
August	17.5	29	
Sept	15.5	25	
Oct	11	19	
Nov	49	14	
Dec	4	9	
Annual	11.5	21	

pressure deficit, and it is for this purpose only that we exploit these calculated values in the latter discussion. Almost identical values were calculated using monthly mean air temperatures and relative humidity data for Zaragoza (Biel and García de Pedraza, 1962).

Soils

No detailed soil information is available from the site where yields were collected, although studies of other soils in this area typically indicate a rooting depth of 50 cm and an 'available' water-holding capacity (between soil water potentials of –30 and –1 500 kPa) of ≈ 90 to 100 mm (Alberto *et al,* 1979; Torres, 1983). Roughly half of this water can be considered readily available in the sense that soil water deficits less than this magnitude would not be expected to limit plant growth. Soils in this region are mostly alkaline (average pH in water 7.7–8.5) with low organic matter contents (< 1.5%). Total carbonate content can exceed 35% (Montañés *et al,* 1991). Rooting depths of terrace soils may be limited by the presence of limestone layers (Alberto *et al,* 1982) and on sloping sites by the variable depth of deposited material from upslope erosion. In the latter situation, soil loss is a serious problem (Arrúe and López, 1991) and terracing is common for both soil and water conservation.

CULTURAL PRACTICES

Records of grain yields were obtained from a commercial farm ≈ 40 to 50 km west of Zaragoza (41° 39'N, 1° 00' W) in the Los Monegros area (fig 1). This same data set was also used by Alberto and Machín (1978) to demonstrate the strong correspondence between annual rainfall and grain yields.

As is traditional in this area, wheat was cultivated using a crop-fallow rotation *(año y vez).* Farming operations usually being in January or February with deep tillage using a moldboard plough. In May or June a second lighter tillage operation is carried out. The fields are then not ploughed again until the end of September or early October when seedbed preparation is carried out prior to sowing (de los Ríos, 1982). Sowing generally takes place in October or early November. Tillering occurs in early January, anthesis in mid-to-late April and harvest between the 10th and 30th of June. Nitrogen applications have not been common practice.

RESULTS AND DISCUSSION

Rainfall

Spectral analysis of the 1941–1989 time-series of monthly rainfalls revealed no patterns or significant harmonics. On the other hand, conventional statistics of the monthly values (table I) revealed several important features of the rainfall pattern. Firstly, and in contrast to many other semi-arid regions, we note the uniformity of average monthly totals and the absence of any well-defined rainy season. A second feature is the high between-year variability as characterised by SDs which are comparable in magnitude to the average monthly totals. Figure 3 shows a histogram of the average monthly rainfall distribution. Only May departs significantly from this general exponentially-decreasing pattern of rainfall totals by having a more symmetrical distribution, peaking at 40–50 mm.

In each month there is a significant probability of having either an extremely low amount (< 10 mm) or no rain at all (table I). Evaporation of soil or foliage wetted by infrequent small showers occurs rapidly and has little effect on soil or plant water status. It is only the occasional large events that contribute significantly to soil water storage. The final 2 columns in table I attempt to emphasise such rainfall events – monthly totals > 50 mm and the probability of rainy days within each month with a rainfall ≥ 30 mm. This is an arbitrary threshold which is approximately equal to the average monthly rainfall. There is a significantly higher probability

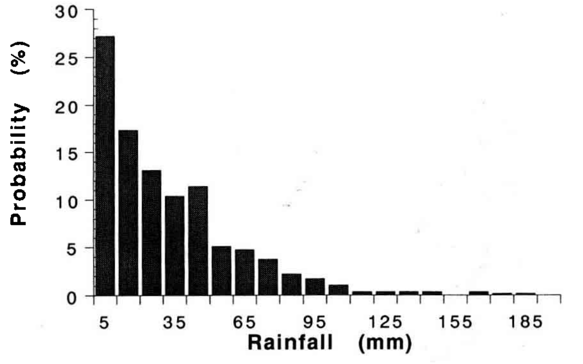

Fig 3. Histogram showing the averaged probability of monthly rainfall totals falling within 10-mm intervals.

of such events in May and in September. The former benefits the post-anthesis grain-filling period whilst the latter which occurs just prior to sowing may also be useful, although the potential for evaporation is high in this period.

Potental evapotranspiration

It will be seen that most of the fluctuations in yields can be ascribed to differences in rainfall; and on an annual or seasonal time scale, this variable also limits evapotranspiration. Under the dryland conditions of interest in the current study, potential evaporation has only a notional value as there is little prospect of high evaporative demands being satisfied for long periods. Nevertheless, some brief comment is required on our use of the Priestley and Taylor (1972) method to estimate the likely water use under well-watered conditions. In temperate regions, this simple empirical method has enjoyed considerable success. In New Zealand, for example, McNaughton *et al* (1979) found daily and weekly estimates to agree with Bowen ratio-energy budget measurements to within ± 15% and ± 5% respectively. Scotter *et al* (1979) and McAneney and Judd (1983) also found agreement between measured and estimated water extraction from pastures.

The Priestley and Taylor method does not account for advection, and finding an operational way of dealing with this effect remains an unresolved problem for local advection theory. Lysimeter measurements from locally well-watered grass in the Rhone Valley clearly show the magnitude of possible advective effects with evaporation rates on occasions exceeding twice the Priestley and Taylor predictions due to *Mistral* winds and regional drying (Seguin, 1977). In Aragon, *Cierzo* wind events may well play a similar role to that of the *Mistral*. However, within a large area (250 ha) of irrigated land on the Crau Plain (northwest of Marseille), the accumulated daily evaporation measured over 100 d was almost exactly that predicted by the Priestley and Taylor method (Seguin *et al,* 1982). The Crau is also subject to the *Mistral*. Thus the performance of the Priestley and Taylor method does seem to provide an acceptable average prediction of water consumption from well-watered crops even in a semi-arid region as time and space scales increase.

Water balance

The nature of the rainfall (R) distribution in this region (see earlier discussion), means that drainage and, on flat sites, runoff can usually be neglected. Thus at a good first approximation, the soil water budget simplifies to:

$$R \approx ET + \Delta S = T + E + \Delta S$$

where ΔS is the change in root zone soil water storage over the time period in question. In a later discussion, regression analysis will be employed to examine relationships between yields and seasonal or annual rainfall totals with the assumption that R and ET are equal, *ie* that on these time scales ΔS is negligible. The corollary to this is that:

$$T_T = ET_T - E_T \approx R_T - E_T$$

where subscripts denote seasonal totals. Substituting for T_T from equation [2], we obtain:

$$E_T \approx R_T - Y_T\,\overline{(e^* - e)}/k_d$$

or

$$R_T \approx R_T - (Y_G/\beta)\overline{(e^* - e)}/k_d \qquad [3]$$

where Y_G is the grain yield and β the harvest index. In principle, this approach allows the seasonal E to be estimated from DM and rainfall totals to the extent that seasonal drainage and runoff losses can be safely assumed to be minor.

A simple geometrical interpretation of equation [3] is possible. Grain yields are first plotted as the dependent variable against seasonal rainfall as in figure 5. A line of slope $\overline{(e^* - e)}/\beta k_d$ from any point will intercept the rainfall axis to give the seasonal soil evaporation E_T. T_T is obtained from the projection of the line on the rainfall axis (*ie* = $R_T - E_T$). Routine use of equation [3] demands measurements of the daily vapour pressure deficit. In absence of such data, we must content ourselves in the present case with estimating long-term average values of E_T and T_T.

Relationships between yields and rainfall

Prior to attempting to evaluate individual components of the water budget, we first examine the dependence of yields on rainfall and the effectiveness of the fallow period in terms of its contribution to subsequent plant growth. The remarkable variability in annual grain yields and their close relationship with fluctuations in the seasonal (October to May inclusive) rainfall is illustrated in figure 4. The reasons for our use of the seasonal rainfall (R_T) and the neglect of rainfall accumulated during the fallow period will emerge in later discussion. Yields are low compared with the 7 500 kg/ha possible under irrigation and with heavy nitrogen treatments (Experimental Farm Records, Estación Experimental de Aula Dei). There are no years when yields are high and seasonal rainfall low. Similarly low seasonal rainfalls always correspond to low yields. This high correspondence between the 2 time-series suggests that at this site, either because of rainfall or soil characteristics, storage of rainfall accumulated over the 18-month fallow period is relatively unimportant compared with within-season precipitation. This could be due either to a low soil water holding capacity at this site and/or poor control of weeds. If this were not the case, then recharge during the fallow period would act to buffer or smooth yields, and reduce their evident dependence on R_T. Figure 5 illustrates more directly the relationship between grain yield (Y_G) and R_T and results in the following regression statistics:

$$Y_G = 6.94\ (\pm\ 0.86) R_T - 670 (\pm\ 228) \qquad [4]$$

The relation has a coefficient of determination (r^2) of 0.66 and a residual standard deviation about the line (*rsd*) of 447 kg/ha. For $R_T \approx < 100$ mm, there is no harvestable yield. The physical interpretation of this rainfall threshold, which was not satisfied in 2 of the 35 years, will be discussed in the next section.

The importance of rainfall during different parts of the season was investigated *via* a series of linear regression analyses of grain yields *versus* the accumulated seasonal rainfall from the beginning of October. Changes in r^2 and *rsd* as an increasing proportion of the season's total rainfall is included are shown in figure 6. The best predictor of final yield appears to be the accumulated rainfall between October 1 and May 31 and it is this rainfall variable that is plotted in figure 4. We call this the 'seasonal rainfall' (R_T) as it encompasses the duration between seedbed preparation and maturation (see *Cultural practices* section). The inclusion of September's rainfall in the analyses actually decreased the *rsd* slightly, probably because the evaporative demand is still high at that time of the year compared with average monthly precipitation (table I). Similarly, the inclusion of the July rainfall during maturation did not improve the statistics.

If the local gradient or slope of the lines in figure 6 is interpreted as some measure of the sensitivity of final yields to rainfall in the corresponding period of the growth cycle, then the October through December period is clearly important. While the dependence of successful emergence on surface wetting by rainfall during this period is obvious, other influences must be acknowledged. The first is that in the absence of further significant rain in January and February, growth must occur using water stored in the soil profile during this early period whilst the soil is bare. This becomes more important if the fallow period was ineffective. On the other hand, in the case of a dry autumn, sowing and seedbed preparation may be delayed and several studies note the decrease in yields that occur with delayed sowing (French and Schultz, 1984; Cooper *et al*, 1987). Figure 6 also implies that rain in April is

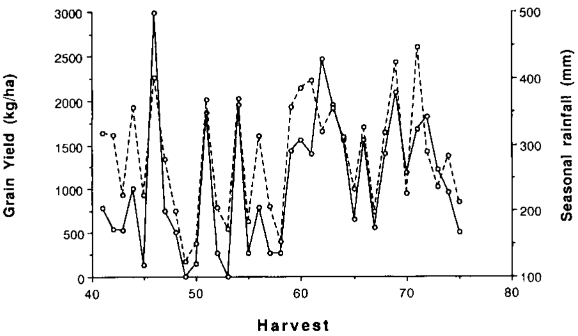

Fig 4. Time series of grain yields (solid line) and seasonal rainfall (dashed line).

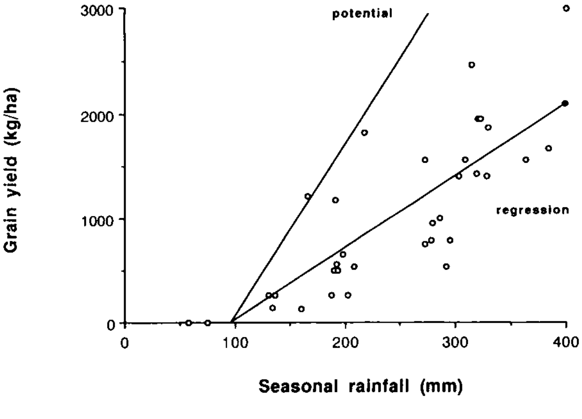

Fig 5. Grain yields *versus* seasonal rainfall. The slope of the upper line gives the average transpiration efficiency in this climate. The lower line is the regression relation (equation [4]).

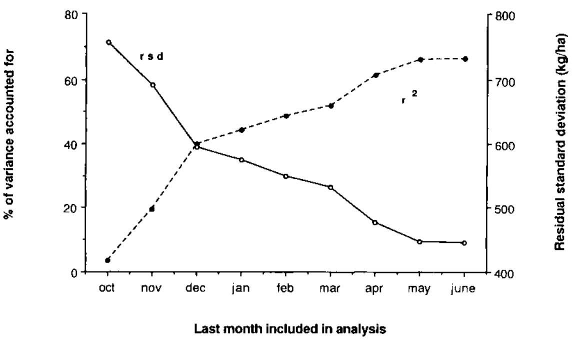

Fig 6. Change in regression statistics as grain yields were regressed against the accumulated rainfall since the beginning of October. The abscissa denotes the last month's rainfall included in the analysis.

important in the latter stages of leaf area development and DM accumulation. This is in accordance with the observation of local farmers that good rains in April lead to a good harvest (Faci, personal communication). We note that successive monthly rainfall totals are very poorly correlated with each other.

The same technique of successive regression was employed to elucidate the relation between grain yields (Y_G) and rainfall accumulated for different proportions of the preceding fallow period. The improvement was slight with the best results being obtained between grain yields and the 12-month period between June to May inclusive (R12):

$$Y_G = 5.81(\pm 0.70)R_{12} - 1\,067\ (\pm 269) \approx 5.8(R_{12} - 184) \quad [5]$$

with an r^2 of 0.69 and rsd = 492 kg/ha. Note that R_{12} includes R_T. Going further back into the fallow period, the 2 variables become less and less related until there is little correlation between yields and the total 24 month rainfall (r^2 = 0.37, rsd = 622). This result is not unexpected, given the strong direct linkage between Y_G and R_T manifest in figure 4.

Water-use efficiency

It is instructive to rewrite [4] as:

$$Y_G \approx 7(R_T - 100) \quad [6]$$

It is usual (Hanks *et al,* 1969; French and Schultz, 1984) to interpret the intercept (100 mm) on the abscissa as soil evaporation. In a slight departure from common practice, we assign this 100 mm as the minimum evaporative loss. This is the unavoidable loss given an annual row crop which has a significant proportion of bare soil during the early part of the season. Depending on the season and leaf area development, evaporative losses may be greater (but never less) than this figure, which comprises 40% of the average seasonal rainfall (255 mm). While there is considerable scope for variation in this value depending on site, seasonal and rainfall characteristics, it clearly represents a significant proportion of what is, in Mediterranean regions at least, a very limited resource. On an annual basis, the intercept of equation [5] amounts to 184 mm or ≈ 50% of the annual rainfall.

We now attempt to estimate the average total evaporative loss from this soil along the lines suggested by equation [3]. An average seasonal $(\overline{e^* - e})$ of 556 Pa was estimated (see *Climate* section) for the January through May period of maximum dry matter accumulation. Substituting this value into equation [2] and using a k_d of 3.1 Pa (Wilson and Jamieson, 1985), we obtain a potential yield of 56 kg•ha^{-1} per mm transpiration for DM production. If the average harvest index is assumed to be 0.3 (average value obtained in a similar climate in South Australia by French and Schultz (1984)), then the potential transpiration efficiency for grain yield is 16.7 kg•ha^{-1}•mm^{-1}. That this figure is in satisfactory agreement with the slope of the 'potential' line (15 kg•ha^{-1}•mm^{-1}) shown in figure 5 gives some confidence in the use of equation [2]. This maximal line represents the boundary which the data does not exceed and also represents an upper limit to water-use efficiency in this climate. French and Schultz (1984) also used this approach to estimate potential transpiration efficiency under South Australian conditions. Variation in published values (15.8 to 23.4 kg•ha^{-1}•mm^{-1} for grain production) is attributable to differences in both mean seasonal vapour pressure deficits and harvest indices.

The water use efficiency of grain production after discounting the 100 mm minimum soil evaporation approached the calculated average yield: transpiration ratio in only 3 out of 35 years. In other years, E presumably accounted for a greater proportion of ET, reflecting reductions in growth due to factors other than water such as extremes of temperature, effects of pests and diseases, and nutritional deficiencies which may restrict leaf area development. We recall that the DM: transpiration ratio is constant (Tanner and Sinclair, 1983 ; Wilson and Jamieson, 1985) and this will also be true for grain production if the harvest index does not vary greatly. While typical values of the harvest index have been adopted for this study of historical yields, measurement of this quantity is recommended in future investigations.

We now estimate the average transpiration from the ratio of the yield: transpiration ratio (slope of the potential line in fig 5), and the regression equation representing the average condition (equation [6]):

$Y_G/T_T = 15$ and $Y_G/(R_T - 100) \approx 7$

to obtain:

$$T_T \approx 0.47(R_T - 100) \quad [7a]$$

and therefore:

$$E_T \approx R_T - T_T \approx 0.53R_T + 47 \quad [7b]$$

After substituting for an average R_T of 255 mm, we find that on average E accounts for some 70% of the seasonal rainfall. Note that these evaporative losses also include evaporation of intercepted rainfall directly from foliage surfaces. Cooper *et al* (1987) cite studies in Syria, where measured losses from evaporation ranged from 35 to 55% of E_T attaining 75% in the case of an unfertilised barley crop. We speculate that under traditional cultural practices, where fertiliser applications were not common, low fertility would often limit yields in the Los Monegros and La Ribera del Ebro-Zaragoza areas, particularly in years with higher rainfall.

CONCLUSIONS

Under the climatic conditions of Central Aragon, wheat yields are closely related to seasonal rainfall. The evidence for justifying a fallow period on the basis of its contribution of stored water to subsequent yields is not strong. This may be due to soil characteristics, shallow rooting and/or ineffective weed control. The uncertain nature of the rainfall distribution and the absence of any well-defined rainy season must also be important contributing factors.

The proposal that the constancy of the transpiration efficiency (Tanner and Sinclair, 1983) be exploited to calculate transpiration from yields departs from conventional practice. Traditionally, equation [2] or its predecessors (*eg* de Wit, 1958) have been used to calculate DM production from water balance measurements. In reversing this procedure, we take advantage of the relative ease of measuring yields and the subsequent estimation of transpiration follows directly. In many semi-arid regions, evaporation can then be calculated by difference from the seasonal rainfall provided drainage or runoff losses can be neglected. Routine use of this methodology would require measurements of vapour pressure deficit and harvest indices (or total DM). Because of the importance of the former, we should take cognisance of the comment by Butler (1992) regarding the need to measure humidity rather than make assumptions about it. Similar sentiments have also been expressed by Monteith (1986).

In applying the above methodology to central Aragon, we calculate an average potential grain yield: transpiration ratio of 16.7 kg•ha^{-1}•mm water transpired. This potential was approached in only 3 or 35 years. A high proportion of the seasonal rainfall (70% on average) is estimated as being lost either by evaporation or by weed transpiration. This result is consistent with the low average yields. We speculate that leaf area development is often limited by low fertility. These conclusions will serve as working hypotheses for experimental investigations of crop water relations currently in progress.

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