Yield-rainfall relationships in cereal cropping systems
in the Ebro River valley of Spain

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Abstract

Wheat and barley yields from three farms in the Ebro River valley are shown to be strongly dependent on seasonal rainfall, particularly that during November - January and March - May of the cropping season. In the driest farm, in Monegrillo, Zaragoza province (seasonal rainfall 250 mm), yields increased by ca 5.9 (wheat) and 9.4 (barley) kg ha⁻¹ per mm of extra rain during the entire cropping season, taken as October - May inclusive. The other farms, at El Canós and Selvanera in Lleida province, had seasonal rainfalls of 364 and 334 mm, and yields of barley increased by 4.3 and 9.0 kg ha⁻¹ per mm of extra rain in the cropping season, taken as September to May inclusive.

In Monegrillo, cereals are grown in a cereal - fallow rotation. Normal fallowing (duration 17 months), compared to minimum fallowing (5 months) increased the calculated water content of the profiles of the dominant soils to a depth of 100 cm by 19 mm. This extra water was estimated to benefit yield by 7.0 % (wheat) and 6.2 % (barley), raising the average yields of crops greater than 300 kg ha⁻¹ to 1222 and 1522 kg ha⁻¹ respectively. Agronomic practices in Monegrillo during the fallow should focus on means of increasing the proportion of the rain stored in the profile during the fallow. At all three locations, decreasing water evaporation from the soil during the cropping season would likely benefit yield.

Keywords: wheat; barley; yield; rainfall; soil water; fallow; dryland farming

1. Introduction

Most wheat and barley in Spain is grown under rainfed conditions in Castilla y León, Castilla la Mancha, Aragón and Cataluña. Yields are low by comparison with those in the more humid countries of Europe and vary markedly from year to year and with location. The central part of the Ebro valley of northeast Spain is especially arid and is marginal for the production of these crops. It is generally supposed that the variation in yield in the area is caused principally by variation in the amount and temporal distribution of rainfall during the growing season (Alberto and Machín, 1978; Martí Ezpeleta, 1992; McAneney and Arrúe, 1993; Cantero-Martínez et al., 1995; López and Arrúe, 199x).

Yield-climate, and especially yield-rainfall relationships have been the subject of many studies. In the arid areas of Syria where yields of barley and seasonal rainfall are similar to those of the central Ebro valley, Van Oosterom et al. (1993) found that variation in seasonal rainfall (October - April) accounted for 50-60 % of the variance in grain yield, rainfall during December and January and April making the most contribution to yield variation. In contrast, Musick et al. (1994) found no relationship between yield of wheat and seasonal evapotranspiration in the dryland conditions in Bushland Texas although yields and seasonal evapotranspiration (dominated by seasonal rainfall) were similar to those encountered in the Syrian study. However, when the data for irrigated and dryland crops were analysed together, seasonal evapotranspiration accounted for 74 % of the variance in yield. An earlier study at the same location (Army et al., 1959) showed that seasonal rainfall accounted for ca 65 % of the variation in dryland wheat yield.

In this paper we report yield-rainfall relationships assessed from data on measured yields from three farms over periods which range from 16-56 years. The farms are in the central part of the Ebro valley of northeast Spain (Fig.1). One farm is in Los Monegros, where cereals are grown in a cereal - fallow rotation. Our analyses allowed us to estimate the benefits to yield from water stored in the soil during the fallow. For this, the amount of water present in the profile at sowing was estimated with a physically based simulation model (Austin et al., 199x), using appropriate soil and climatic data. The other two farms are in La Segarra, a less arid area than Los Monegros. In La Segarra, cereals, principally barley, are grown annually without fallowing.

2. Materials and Methods

Los Monegros

Los Monegros region of the Ebro basin is one of the most arid areas of Spain (and Europe) in which dryland agriculture is practised. The mean annual rainfall varies with location from 300-500 mm (Martí Ezpeleta, 1992), but rainfall at a given location varies greatly and monthly rainfall is even more variable. As in most of north-central Spain, rainfall is bimodally distributed, with peaks in April-May and September-October, though these peaks are not very marked. Barley is the principal dryland cereal crop grown in Los Monegros, but durum and bread wheat are grown in the more favourable locations. In contrast with much of the rest of Spain's drylands, which are now cropped annually, a cereal fallow rotation is normal in Los Monegros. It might be supposed that the soils are fallowed to improve the water available for the following crop, but the calculations of Austin et al. (199x), and the measurements of López et al (1996) suggest that the benefits from water storage during the fallow are quite small. Estimated average yields of barley and wheat in Los Monegros are less than 2 t ha^{-1} , and are strongly dependent on seasonal rainfall (Martí Ezpeleta, 1992).

Records of wheat and barley production and cropped areas were available from a farm ($00^{\circ} 25'W$, $41^{\circ} 38'N$, 430 m a.s.l.) close to Monegrillo for most years during the period 1941-1996. In the early years of the period a minimum of 300-400 ha of wheat and of barley were harvested annually. With improved mechanisation, this area has

approximately doubled. There have also been changes in cultural practices.

Mouldboard ploughing was abandoned in 1986 in favour of chisel ploughing to a depth of 30-35 cm. Since the early 1960's moderate amounts of nitrogen and phosphorus fertiliser have been used: currently the applications are $25 \text{ kg ha}^{-1} \text{ N}$ and $55 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$. Reference evapotranspiration in Monegrillo is close to 1050 mm y^{-1} (Martínez-Cob et al., in press). Further information on aspects of the climate and cropping system in the Monegrillo area is given by McAneney and Arrúe (1993).

The soils on most of the farm are silty clay and silty clay loam Xerochrepts, with a depth exceeding 100 cm. For the calculation of water storage in the profile we have assumed that the effective rooting depth is 100 cm. Soil samples were taken from three representative sites on the farm. The samples were analysed for soil texture, bulk density and porosity. The results were used to estimate water-related soil physics parameters using pedotransference functions (Rawls et al., 1992). These characteristics were assumed for running the simulation model (Austin et al., 199x) which was used to calculate the water content of the soil at sowing (see below). The most common soil type (Mosen), occupies ca 50% the area of the Monegrillo farm. Of the other types, Valle occupies ca 25 % and Polvorosa occupies ca 10 % of the farm area.

Monthly rainfall from the Monegrillo pluviometric station ($00^{\circ} 25' \text{ W}$; $41^{\circ} 38' \text{ N}$) was used in calculating the regressions. Daily rainfall was required for the calculation of the water content of the profile at the end of the fallow and these records were taken

from the same station. For the few periods where daily records were not available from this station, records from one of two nearby stations were substituted.

For the purpose of this paper we took the sowing date in Monegrillo to be 1 December. The actual sowing dates each year were not recorded, but were generally within a month of this date. To estimate the amount of water present in the profile at sowing on 1 December in year n (the crop being harvested in year $n + 1$) we took it that the soil was at permanent wilting point after harvest in June of year $n - 1$. Using historical daily rainfall from July of year $n - 1$ to the end of November in year n , we computed the amounts of water in the profile to a depth of 100 cm on 1 December of year n . These calculations were done for the minimum fallow period of 5 months, and for the normal 17 month fallow. The calculations were made with the model described in detail by Austin et al., 199x. Apart from daily rainfall, the other variables required were mean monthly evapotranspiration (ETo) and various soil physical characteristics. ETo was obtained from the nearest meteorological station (Montañana, 35 km west of Monegrillo) where all the data needed to compute it were available. The soil physical characteristics were those needed to calculate water flow between soil layers based on Darcy's law. Evaporation from the bare soil surface (Es) was calculated from an empirically derived equation relating Es to ETo as a function of the moisture content of the upper 50 mm of soil. Each simulation was started on 1 July, when the moisture content of the entire 100 cm of the soil profile was taken to be that corresponding to wilting point (-1.5 MPa). It should be emphasised that the outputs from the model used in the statistical analyses were the *amounts* of water present in the profile at sowing, and not the *storage* during the fallow, as defined by Austin et al., 199x).

La Segarra

La Segarra is a semi-arid area varying in altitude from 250 to 500 m a.s.l. Annual rainfall varies from 250 to 600 mm, but there is substantial spatial variation, the southeast part of the region receiving ca 350 mm, and the higher altitude, northern part, ca 600 mm. Most of La Segarra is devoted to field crops, principally barley. Fallowing was abandoned in the 1950's and cropping is now annual. We have analysed yield data from two farms in La Segarra.

Records from El Canós were available from 1959 to 1997. This farm (01° 17'E, 41° 41'N, 435 m a.s.l.) is located in the more arid part of La Segarra. It is 100 ha in extent and barley is grown without rotation. The soils are Xerochrepts, Torriorthents and Xerofluvents, varying in depth from 30 to 120 cm. Since 1959 land has been prepared for sowing by tine harrowing. Fertilizer is applied annually before sowing in mid October providing 40 kg ha⁻¹ N and 60-70 kg ha⁻¹ of both P₂O₅ and K₂O. A top dressing of 60 kg ha⁻¹ N is applied in spring. Herbicides are always used and fungicides and insecticides applied occasionally, as necessary. Rainfall data were taken from Cervera (540m a.s.l), 2 km from El Canós.

Records from Selvanera were available from 1982 to 1997. The farm (00° 18'E, 41° 50'N, 475 m a.s.l.) is 150 ha and barley in the principal crop with minor proportions of wheat and oilseed rape. The soils are Xerochrepts and Xerofluvents and are somewhat deeper than at El Canós. Since 1982 a conservation tillage system has been practised, since the land is prone to erosion. Barley is sown in late October.

Before sowing, fertiliser is applied providing 50 kg ha⁻¹ N and 60-70 kg ha⁻¹ of both P₂O₅ and K₂O. A top dressing of 60 kg ha⁻¹ N is applied in spring. Crop protection chemicals are applied as for El Canós. Rainfall data were taken on the farm.

Statistical analysis

The analyses comprised the following steps:

1. Regression of yields on years to detect and, if found, allow for any long term linear trends of yield with time associated with technological improvement (agronomy and cultivars).
2. Correlation of yield with monthly rainfall to identify those months during which variation in rainfall significantly influenced yield.
3. Grouping of rainfall into periods corresponding to the vegetative phases of growth and to the grain filling period, and calculation of the regressions of yield on the rainfall during these periods.
4. For Monegrillo only, estimation of the water present in the profile at sowing and the inclusion of profile water as an independent variable in the regressions.

3. Results and discussion

No significant proportion of the variance in yield of either wheat in Monegrillo or barley at any of the locations was accounted for by linear regression on years. This is in sharp contrast to the trends for these crops for the whole of Spain as well as other countries of western Europe. Over the period 1955 - 1990, estimated yields of wheat and of barley throughout Spain have increased by 52 ± 5 and 34 ± 5 kg ha⁻¹ per annum, accounting for 77 and 53 % respectively of the variation in yield over this period (source: Anuario de Estadística Agraria del Ministerio Agricultura, Pesca y Alimentación published by the Government of Spain). These comparisons suggest that the environments in the Ebro valley locations we have examined are too arid for yields to have benefited from improvements in agronomy and improved cultivars that have been achieved elsewhere in Spain, and/or that improved agronomic practices and cultivars appropriate for the area have not been developed.

The mean yield of wheat (total production divided by the number of seasons) at Monegrillo was 898 kg ha⁻¹ (56 seasons) and that of barley 1325 kg ha⁻¹ (43 seasons). Simple correlations of yield and rainfall (Table 1) show that yields of wheat and barley were significantly correlated with rainfall during the three months November - January and the two months April - May. Variation in rainfall during other months was weakly or inconsistently associated with yield. It should be noted that the standard deviation of monthly rainfall was similar to mean monthly rainfall, and that the standard deviation did not vary greatly with month. Thus the weak correlation between monthly rainfall

and yield for the months August - October, February and July could not have been caused by low variability of rainfall in these months.

At El Canós, where sowing is earlier than in Monegrillo, and September and October are wetter than in Monegrillo, the mean yield of barley was 2358 kg ha⁻¹. The simple correlations of yield with rainfall by month are shown in Table 2. The average yield of barley at Selvanera was 3664 kg ha⁻¹. The correlations between yield and monthly rainfall at Selvanera are not presented as they were based on only 16 years data.

Tables 3A and 4A show the multiple regression coefficients of rainfall on yield for rainfall grouped into three periods: October - December (September -December in the locations in La Segarra), which we considered would be available for the establishment and early growth of the crops; that during January - March, important for the main phase of growth and for the development of yield potential; and that during April and May, important for grain filling and so for the realisation of yield potential.

In Monegrillo, the inclusion of these three terms accounted for about half of the variance of yield of wheat and barley, and each term was statistically significant (Table 3A). When the rainfall during the three periods was aggregated into seasonal rain, regression of yield on this single term also accounted for about 50 % of the variance in yield of both crops (Table 3B and Fig.2). Barley was more responsive than wheat to rain, especially to rain during October - December and April - May, and the seasonal coefficient was 60 % greater for barley than for wheat. These differences support

the generally held view that barley is better adapted than wheat to very dry rainfed conditions.

Table 3B gives the estimated crop rainfall for zero yield of wheat and barley in Monegrillo. This latter statistic has been taken as equivalent to the minimum evaporation from the cropped soil during the crop season, and amounts to approximately 52 % of the seasonal rainfall. However, this interpretation cannot be strictly correct, because even in years where no grain is harvested, there will be a significant biomass and leaf area, from which there will be transpiration.

For Monegrillo, where a cereal-fallow rotation is practised, Table 3C gives the values of the coefficients of the multiple regression on yield of rainfall during December - March and that for April - May, and for the estimated water content of the profile of the Mosen soil at sowing after the normal 17 month fallow. Inclusion of these three terms accounted for 55 % (wheat) and 44 % (barley) of the variation in yield of these crops, and each of the three terms was significant at $p < 0.05$. Of note is that the coefficients for profile water content are greater than those for the rainfall during October - December (given in Table 3A). Presumably this is because much of the water in the profile at sowing is 'used' in transpiration, benefiting photosynthesis, while the rainfall coefficients represent yield gain per mm of (transpiration+ evaporation) from the soil surface, and when they are wet, from leaf surfaces. This evaporation, which has been estimated to be at least 50 % of seasonal evapotranspiration from the crop in Mediterranean climates (Cooper et al., 1987; our estimate: 52 %, though up to 70 % in Monegrillo according to McAneney and Arrúe, 1993) does not benefit yield, or benefits

it only marginally by increasing the atmospheric vapour pressure and so the ratio of photosynthesis to transpiration. The large coefficients for the December - March rainfall may be taken to indicate the critical importance of rain during this period for the establishment of yield potential.

We estimated the benefits to yield in Monegrillo from water stored in the soil during fallowing using the coefficients given in Table 3C (wheat, 6.88; barley, 9.96, for the Mosen soil, and the corresponding coefficients for the two other soils) and from the increases in soil water content resulting from the fallow year. The mean increase in profile water content of the Mosen soil as a consequence of fallowing was estimated to be 19 mm over 49 seasons (standard deviation 12 mm). Because the water content of the profile at sowing was strongly dependent on the rainfall in the two preceding months (Austin et al., 199x), and these months were, by definition, common to both annual cropping and the cereal - fallow rotation, the water contents at sowing with both cropping systems were highly correlated ($r = 0.95$). The yield increase from fallowing was calculated for each year and soil type as the product of the coefficients and the water content of the soil after the 17 month fallow minus that in the profile after the minimum 5 month fallow in that year. These calculations were done for those years for which yields and the estimates of water storage were available. Assuming that yields lower than 300 kg ha⁻¹ (twice the seeding rate) were crop failures, we calculated the mean yields with and without fallowing. The results are summarised in Table 5. For both wheat and barley, fallowing increased yield (by averages of 94 and 85 kg ha⁻¹ respectively). Fallowing slightly decreased the number of crops which were considered to have failed.

In El Canós, the mean seasonal rainfall (September - May inclusive) for the period 1959-1997 was 364 ± 98 mm. There were 39 years when both yield and monthly rainfall were available, the joint regression of the three rainfall terms on yield accounted for 31% of the variation in yield. The coefficients are given in Table 4A. Regression of seasonal rainfall on yield accounted for 34% of the variation in yield (Table 4B).

In Selvanera, yield and rainfall data were available for the entire period 1982-97. Mean seasonal rainfall was 333 ± 90 mm. Table 4 shows the values of the coefficients of the regression of rainfall on yield. At this location, rainfall accounted for 46% (multiple regression, three terms) and 39% (seasonal rainfall) of the variation in yield.

The coefficients given in Tables 3B and 4B may be equated to water use efficiency, if it is assumed that there is no drainage during the crop season. Simulation studies (Austin et al., 199x) showed that even when the soil was not cropped, there was very little drainage out of the rooting zone (the upper 100 cm). Water use efficiency in units of kg grain m^3 of rain or evapotranspiration can be derived from the coefficients in Tables 3B and 4B by dividing by 10. For wheat in similar environments Army et al. (1959) found values of 0.4-0.6, Van Oosterom et al. (1993) 0.8-1.1 and Musick et al. (1994) values, based on seasonal evapotranspiration, of 0.3-0.8. Our values range from 0.43 to 0.94, depending on species and location, and are thus within the range found for wheat in the above studies. Similar values have also been reported by Cantero-Martínez et al. (1995) and López and Arrúe (199x) for locations in the Ebro River valley. In Monegrillo, barley was more efficient in water use than wheat, as

expected. Of the locations in La Segarra, the water use efficiency of barley at the cooler location (Selvanera) was greater than at El Canós, also as expected.

4. Conclusion

In the very harsh environment of the farms studied, especially Monegrillo, it is clear that water is a major limitation to cereal production, as also reported by McAneney and Arrúe (1993) in their study based on a subset of the Monegrillo data we have analysed. Our calculations indicate that in Monegrillo, normal, long fallowing increases the water content of the soil profile at sowing time by an average of only 19 mm, by comparison with that after the minimum five month fallow. The extra water was calculated to increase yields by 7.0 % (wheat) and 6.2 % (barley), and to slightly decrease the risk of crop failure. These calculations assume no other benefit to yield other than that resulting from increased soil water content at sowing, and so could underestimate the actual yield gain from fallowing. On this basis, cereal production from a given area of land over a run of years would be greater with annual cropping than with a cereal - fallow rotation.

Regression models for summarising yield-rainfall relationships are not fully satisfactory for the dry conditions of the Ebro valley. This is because prolonged drought (little or no rain for *ca* three months) during any stage of growth causes crops to fail. In this circumstance, even though rain may be plentiful during the other months of a growing season, it will be ineffective for yield. The consequence is that the proportion of the variation in yield accounted by multiple regression of yield on rainfall will be lower than would be the case if the effects of rainfall during the different growth stages were modelled to be conditional on the amounts of rain during other stages of growth. This limitation does not apply to dynamic simulation models, which

in principle could be used to estimate the dependence of yield on rainfall at different stages of growth.

Any means of conserving water either during the fallow or during the cropping season would benefit yield. In Monegrillo, the yield gains would be ca. 7 (wheat) and 10 (barley) kg ha⁻¹ grain per mm water conserved, but probably more if accompanied by improved fertilisation, and pest and disease control.

For all three locations yield was more sensitive to rainfall in the early and late stages the crop cycle than during February and March. This was an unexpected result because February and March are dry months relative to the other months of the crop cycle. However, rainfall during February and March is somewhat less variable (Tables 1 and 2) than in other months. It may be for this reason that it is difficult to demonstrate as strong a dependence of yield on rainfall, even though yield may intrinsically be as sensitive during this period as before or after it. Another reason for the relative insensitivity of yield to rainfall in February and March may be that these are months with low ETo, and when the soil may be expected to have been recharged with water from autumn rain.

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Table 1.

Mean monthly rainfall (1941-1996) in Monegrillo and its standard deviation and simple correlation coefficients between cereal yields and monthly rainfall.

Month	Mean rainfall (mm)	Standard deviation of rainfall (mm)	Coefficient of correlation between rainfall and:	
			wheat yield (n=56)	barley yield (n=43)
August	23.5	18.9	0.135	0.181
September	35.5	36.6	-0.050	0.028
October	36.4	35.1	0.044	0.127
November	30.2	33.2	0.305	0.214
December	27.3	25.3	0.460	0.534
January	23.6	24.5	0.390	0.330
February	23.7	23.1	0.138	0.014
March	23.9	24.1	0.301	0.206
April	36.6	35.7	0.306	0.236
May	49.6	29.5	0.332	0.477
June	34.6	28.7	0.134	0.116
July	20.5	24.2	0.087	0.029
Season ¹	250.1	83.9	0.753	0.717
Annual	365.2	97.2	-	-

¹October to May, inclusive

Table 2.

Mean monthly rainfall (1959-1994) in Cervera, its standard deviation and coefficients of correlation with yield of barley at El Canós.

Month	Mean rainfall (mm)	Standard deviation of rainfall (mm)	Coefficient of correlation between rainfall and yield (n=39)
August	37	26	0.163
September	52	38	0.128
October	58	48	0.136
November	40	30	0.206
December	34	30	0.248
January	30	28	0.346
February	22	16	-0.150
March	34	33	0.266
April	40	27	-0.032
May	55	42	0.399
June	42	30	0.103
July	17	13	-0.056
Season ¹	364	98	0.598
Annual	461	114	-

¹ September to May, inclusive

Table 3.

Coefficients of the regression of the given variates on yield of wheat and barley in Monegrillo. Units of the coefficients are $\text{kg ha}^{-1} \text{ grain mm}^{-1}$ rain or water in the profile.

	Wheat (n=56, 49)*		Barley (n= 43, 36)	
	coefficient	s.e.	coefficient	s.e.
A. Rainfall only (multiple regression coefficients)				
October - December	4.33	1.14	7.82	2.05
January - March	8.32	1.64	10.25	3.24
April - May	6.28	1.44	11.47	2.82
B Seasonal rainfall				
October - May	5.89	0.82	9.42	1.49
<i>Estimated seasonal rain when yield is zero, mm</i>	122		139	
C. Rainfall and profile water content (Mosen soil)				
Profile water content at sowing	6.88	1.74	9.96	3.31
Rain, December – March	9.16	1.43	10.87	2.70
Rain, April – May	4.42	1.58	6.73	3.31

* first number relates to coefficients under A and B, second to those under C.

Table 4

Coefficients of the regression of the given variates on yield of barley in El Canós and in Selvanera. Units of the coefficients are kg ha^{-1} grain mm^{-1} rain.

	El Canós (n=39)		Selvanera (n=16)	
	coefficient	s.e.	coefficient	s.e.
A. Multiple regression on rainfall sums:				
September - December	3.63	1.40	9.64	3.82
January - March	4.84	2.12	-0.93	5.68
April - May	4.90	1.93	17.93	7.37
B. Simple regression				
Seasonal rainfall ¹	4.26	0.94	8.98	2.74

¹ Rainfall from September to May, inclusive

Table 5.

Number of crops and yields with a cereal- fallow rotation and estimated number of crops and yields with annual cropping in Monegrillo. See text for explanation of method of calculation.

	Wheat		Barley	
	Number	Yield, kg ha ⁻¹	Number	Yield, kg ha ⁻¹
Number of crop years and yield obtained ¹	49	957	36	1243
Number of crops harvested with cereal - fallow rotation, and yield obtained ²	37	1222	29	1522
Estimated number of crops harvested under annual cropping, and yield obtained ² for the given soils:				
Mosen soil	34	1145	26	1450
Valle soil	27	1122	26	1389
Polvorosa soil	34	1144	26	1446

¹ number of years for which daily rain and yields were available, and the total grain production (including yields below 300 kg ha⁻¹) divided by the number of years

² number of crops with yield greater than 300 kg ha⁻¹, and the mean yield of those crops on the given soils.

Fig.1. Maps showing the location of the Ebro River basin in Spain and of the three farms in the Ebro valley from which yield records were obtained. The map of the Ebro valley shows the course of the Ebro River (dark line) and the boundary of the Ebro basin in Aragón and Cataluña (dashed line).

Fig.2. Relationships between seasonal rainfall (October - May, inclusive) and the yields of wheat (upper graph) and barley (lower graph) at Monegrillo. The linear regressions of best fit are shown: r for wheat, 0.753; for barley, 0.717.