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Effects of rainfall and temperature on the feeding value of barley straw in a semi-arid Mediterranean environment

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SUMMARY

Annual variation in the feeding value of barley straw (*Hordeum vulgare* L. subsp. *vulgare*) is economically significant in the Mediterranean region. The relationship between the feeding value for sheep of several winter-planted barley cultivars and monthly meteorological data was analysed at Tel Hadya, northwest Syria (mean annual precipitation 330 mm) in 11 years. Indicators of feeding value included contents of neutral detergent fibre, acid detergent fibre and nitrogen (11 years), voluntary straw intake by sheep (10 years), voluntary digestible organic matter intake (9 years), *in sacco* dry matter loss and lignin content (8 years), *in vitro* digestibility (7 years) and *in vitro* gas production (6 years). Monthly meteorological data included total precipitation, mean minimum and mean maximum air temperatures.

Conditions likely to decrease grain yield tended to increase the feeding value of straw. Low mean minimum temperature in February, low precipitation in January, February, March and April, and high mean maximum temperature in March, April and May increased one or more indicators of straw feeding value (by both bivariate and multiple regression, $P < 0{\cdot}05$). Precipitation before January affected grain and straw yield but had little effect on the feeding value of straw.

Genotype × year interactions had a meteorological component; the superior feeding value of the straw of locally-adapted cultivars *v.* exotic cultivars was only seen in years with cool or wet springs. This has implications for the genetic selection of crops with better straw feeding value.

Models based on monthly precipitation and temperature, calibrated for locations in the Mediterranean region, can predict the nutritive value of straw and aid the planning of rations for small ruminants.

INTRODUCTION

In semi-arid areas to the east and south of the Mediterranean Sea, sheep obtain a large proportion of their nutrients from the barley crop (*Hordeum vulgare* L. subsp. *vulgare*). The crop may be harvested and fed as straw, stubble and grain, or may be left unharvested for grazing during the spring or summer. Annual precipitation in these areas (henceforward referred to as *rainfall*, to be understood as including dew and snow) has a coefficient of variation commonly exceeding 30%, and has an important effect on barley grain yield (van Oosterom *et al*. 1993). In drought years, although there is a reduction in the yield of grain, the feeding value of straw is generally increased (Capper *et al*. 1988); sometimes grain yields are so low that harvesting is uneconomic and grazing is the only option. Barley is a preferred crop because it can provide feed of some kind even in drought.

In the drier parts of the geographical range of barley cultivation, indigenous mixtures of genotypes (*landraces*) are preferred, as drought reduces their grain yield to a lesser extent than in exotic genotypes (Ceccarelli 1993). The nutritive value of barley straw in semi-arid areas is also enhanced by the generally dry conditions.

An additional source of variation in the nutritive value of straw in these areas is between genotypes of barley; in particular, landraces of barley have straw of generally higher nutritive value than exotic genotypes (Capper *et al*. 1988; Ceccarelli 1993), partly as a result of their exclusively 2-row type (Erickson *et al*. 1982). Site-to-site or year-to-year variation in rainfall affects the nutritive value of straw to an extent exceeding the effect of genotype, often in association with genotype × environment interactions (Capper *et al*. 1988; Goodchild *et al*. 1994).

The unpredictability of genotype × environment interactions in the Mediterranean zone has been considered an impediment to selecting barley genotypes having straw of superior nutritive value in dry environments. In northern climates where meteorological stress is less frequent, the ranking of barley cultivars has been found to be stable for crude protein, *in vitro* digestibility (Erickson *et al*. 1982) and *in sacco* degradability of barley straw (Ørskov 1988). Wright & Hughes (1991) confirmed the stability of *in vitro* and 24-h *in sacco* results in 12 cultivars across eight sites in England and Wales, but cultivar effects were small relative to site × cultivar interactions for cell wall, its constituents, and crude protein. A better understanding of genotype × environment interactions affecting straw feeding value would facilitate the design of effective selection strategies.

In some cereals, including wheat and barley, inhibition of growth by water stress makes plants morphologically more immature (leafier and shorter) at harvest (Capper *et al*. 1988). Where water stress occurs late in growth, the translocation of the products of photosynthesis from leaves and stem to seed is inhibited (Pearce 1983). Both of these phenomena can improve the feeding value of straw. The effects of heat and cold stresses on straw feeding value are less clear (e.g. Deinum 1988). Genotypic differences in susceptibility to stress may be one source of genotype × environment interaction affecting the feeding value of straw.

Meteorological effects on the nutritive value of straw, together with variation in straw and grain supply between wet and dry years, are reflected in wide differences in the market price of straw (F. Bahhady, unpublished, quoted in Rodríguez & Göbel (1994)). The resulting variation in the types of feeds needed to complement the straw nutritionally also increases the difficulty in formulating straw-based rations. In practice, blanket recommendations for formulating rations based on straw can lead to wasteful use of energy-dense feeds in dry years or inadequate animal performance in wet years.

With the increasing frequency of annual feed deficits in arid regions, there would be socioeconomic and animal-welfare benefits in forecasting the quantity and nutrient content of feedingstuffs needed to compensate for shortfalls in the quantity and quality of locally produced feed resources. Farmers would benefit from a simple method for predicting the effect of weather on the yield and feeding value of barley and its by-products, in order to plan whether to feed, sell or store straw, and to decide which feedingstuffs need to be retained or purchased to nutritionally complement rations containing straw. Forecasts would also help those responsible for feedingstuff trade and policy to make better informed decisions. How farmers in aggregate feed their livestock has impacts on market prices of feedingstuffs, on movements of straw and other feedingstuffs between regions and countries, and on the probability of harm to livestock through depletion of feed supplies.

This paper examines in detail the effect of rainfall and air temperature on various measures of the feeding value of straw at one site in 11 years. It also describes broad genotypic differences in the responses of the feeding value of straw to meteorological variables and attempts to relate them to differences in responses of grain yield to drought stress. It discusses the possibility of developing locally-relevant models for predicting the feeding value of straw.

MATERIALS AND METHODS

Meteorological data

Totals of monthly precipitation (*Pptn*, here referred to as rainfall), monthly means of minimum and maximum air temperatures (*Tmin*, *Tmax*), and number of days in which the minimum air temperature was < 0 °C (*Frost*) were obtained for 16 years from the meteorological station at Tel Hadya, Syria (36° 56′ E, 36° 10′ N, altitude 300 m a.m.s.l.). Mean monthly air temperature was calculated as $(Tmin + Tmax)/2$.

Barley crops

This paper analyses the results of an 11-year series of experiments at Tel Hadya designed to measure genotypic variation in the feeding value of barley straw. In each year between two and nine recognized cultivars out of a total of 13 were grown (Table 7). Crops were sown at the rate of 100–120 kg/ha in November or December in a 2-year rotation after food legumes. The soils were Calcixerollic Xerochrepts, typical of northern Syrian soils in having a good water-holding capacity (Loss & Siddique 1994). The only fertilizer application was nitrogen (up to 66 kg/ha), other than occasional triple superphosphate to maintain soil Olsen P at > 10 mg/kg. The crop was combine-harvested at a height of 10 cm when all cultivars in the experiment were mature, except in 1985, 1989 and 1990, when the short, drought-damaged plants were harvested by hand.

Indicators of straw feeding value

Feeding value data were available for straw harvested in the 11 years 1982–86, 1988–90 and 1992–94 (Capper *et al*. 1986, 1988, 1989; Abdel Malik 1994; Goodchild *et al*. 1994, 1995, unpublished; Herbert *et al*. 1994).

Voluntary intake of dry matter (*DM*) *and digestible organic matter* (*DOM*)

The dry matter intake of straw harvested in 10 years was expressed as g/kg $BW^{0.75}$. In each year, the data were derived from between two and nine cultivars of barley that had been individually fed to 3–12 Awassi-breed sheep in 1, 2, 3 or 4 experiments. Sheep were offered 1·2 times the previous day's straw intake, usually for 21 days. In the two years 1989 and 1990, low straw yields curtailed the feeding period, but precision was ensured by concurrently feeding straw harvested in 1988 to other sheep. In the last 10 days of feeding trials for all years except 1990, faecal output was measured by total collection. Yearly means of variables were calculated from experimental results in two stages. First, the voluntary intake for each cultivar–year combination was calculated as a least-squares mean using PROC GLM (SAS Institute 1989), adjusted by covariance on the daily intake of nitrogen (0–23 g/d) and DM (0–344 g/d) in supplementary feeds. Second, year least-squares means adjusted for cultivar were calculated using PROC GLM. Adjusted year means for the voluntary intake of DOM, and DOM in the DM of straw, were likewise calculated in the nine years in which faecal output was measured.

Adjusted year means of the other straw feeding value indicators were calculated where data were available.

Gas production measurements in vitro

Hohenheim Futterwert Test (HFT) measurements (Menke *et al.* 1979) were carried out at Hohenheim University, Stuttgart, Germany, using 0·2-g samples of straw milled though a 1-mm screen (K. Becker, M. Blümmel & N. Borowy, unpublished). Gas production (ml) was recorded at 4, 6, 8, 12, 24, 30, 36, 48, 54, 60, 72 and 96 h. Parameters *a*, *b*, and *c* were fitted to the following asymptotic regression model using PROC NLIN (SAS Institute 1989):

$$\text{Gas Production} = a + b \times (1 - \exp(-c \times \text{IncubationTime}))$$

The more biologically meaningful $a+b$ (gas pool size), rather than *b* itself, was used in subsequent analyses.

DM loss measurements in sacco

For straws harvested between 1985 and 1993, *in sacco* DM loss was measured in seven rumen-cannulated sheep fed a daily diet of 400 g barley straw, 200 g common vetch hay (*Vicia sativa*), 100 g barley grain and 100 g cottonseed cake in a trial lasting 8 weeks; data for the 1994 straws was taken from a later *in sacco* trial of similar design. Samples (3 g) of straw used in feeding trials were milled through a 3-mm screen in a Wiley mill, incubated for 0, 8, 24, 48 and 72 h in 18 × 9 cm nylon mesh bags with pore size 40 µm, washed and dried at 65 °C overnight. The incubations were repeated each week in different sheep, using a balanced incomplete block design. The parameters *a*, *b*, *c*, and *Lag* were fitted to the following model using PROC NLIN (SAS Institute 1989):

$$\text{DMLoss} = a + b \times (1 - \exp(-c \times \text{T}))$$

where T = IncubationTime (h) corrected for *Lag* if *Lag* was > 0 (McDonald 1981). The potential degradability $a+b$ was used in preference to *b* in subsequent analyses.

Other laboratory analyses

These included total nitrogen (N) by the Kjeldahl method, neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) (Goering & Van Soest 1970), and two-stage *in vitro* digestibility (Tilley & Terry 1963). The latter test was modified by the addition of ammonium sulphate (280 mg N/litre) at the microbial fermentation stage to compensate for the low N concentration of samples, and was standardized using two straws of known high and low *in vivo* digestibility. Analyses for 1985–94 straws were performed at least in triplicate under uniform conditions; analyses for N, NDF and ADF in 1982–84 straws were taken from Capper *et al.* (1986, 1989).

Correlation and regression analyses

Bivariate correlation between the 32 meteorological variables shown in Table 1 and yearly means of feeding value indicators was performed, to give an indication of their relative influence. Then an appropriate subset of these variables was selected for use in subsequent analyses. All meteorological variables in this subset had significant correlations ($P < 0.05$) with at least one feeding value indicator, but where two variables (e.g. *Frost* and *Tmin*) had similar patterns of correlation with feeding value, one of the variables was omitted. Third, feeding value indicators were subjected to multiple regression analysis using PROC REG with the MAXR selection method (SAS Institute 1989) against the subset of meteorological variables. Fourth, similar regression analyses were carried out using the yearly mean voluntary intake of each of five groups of barley straw cultivars listed in Table 7.

RESULTS

Meteorological data

The climate of Tel Hadya is expressed as means, standard deviations and some intercorrelations of monthly meteorological data in Table 1. Mean monthly rainfall exceeded 25 mm from October to April, with a coefficient of variation (C.V.) of the order of 50–60 %. The coldest months were January and February (each having *c.* 10 frost events, with a 60 % C.V.); there were no frosts after early April. Between December and March, *Tmin* was strongly and negatively correlated with *Frost*. *Tmin* and *Tmax* rose

Table 1. *Means, standard deviations and correlations amongst monthly meteorological variables in the 16 years 1979/80 to 1994/95 at Tel Hadya, Syria*

	Month					
Estimate	December†	January	February	March	April	May
Rainfall (Pptn), mm	51·7 (23·9)‡	62·8 (31·2)	55·2 (33·5)	39·9 (25·2)	26·2 (19·8)	16·2 (11·3)
Temperatures						
Mean maximum (*Tmax*), °C	12·4 (1·9)	11·1 (1·6)	13·2 (2·3)	17·6 (1·7)	23·9 (2·4)	29·3 (1·8)
Mean minimum (*Tmin*), °C	2·7 (1·6)	1·6 (2·3)	1·8 (1·7)	4·0 (1·8)	7·7 (1·2)	11·8 (1·1)
Frost events (*Frost*), number	7·9 (5·0)	10·6 (6·6)	9·6 (5·6)	4·8 (3·9)	0·3 (0·8)	0·0 (0·0)
Correlation coefficients (14 D.F.)						
Pptn with *Tmax*	−0·17	0·33	−0·27	−0·56*	−0·58*	−0·69**
Pptn with *Tmin*	0·18	0·67**	0·40	0·45	0·16	−0·54*
Pptn with *Frost*	−0·23	−0·69**	−0·19	−0·30	−0·15	
Tmax with *Tmin*	0·43	0·55*	0·44	0·34	0·50	0·53*
Tmax with *Frost*	−0·33	−0·47	−0·543*	−0·40	−0·11	
Tmin with *Frost*	−0·92***	−0·98***	−0·94***	−0·86***	−0·39	

† Total rainfall (mm) for September was 0·5 (S.D. 0·8), October 25·4 (S.D. 24·4) and November 52·6 (S.D. 27·9). *Rainfall* denotes precipitation and includes snow and dew.
‡ Standard deviation (S.D.) in parentheses. * $P < 0·05$; ** $P < 0·01$; *** $P < 0·001$.

Table 2. *Selected monthly meteorological data† in the 11 years for which at least one indicator of barley straw feeding value was measured*

	Year ending										
	1982	1983	1984	1985	1986	1988‡	1989	1990	1992‡	1993	1994
Precipitation, mm											
Sept to Dec	129·6	107·7	98·7	148·2	91·7	192·5	185·9	123·6	172·2	99·4	77·7
January	56·6	17·1	49·3	126·3	71·9	84·7	10·0	30·4	62·3	57·8	112·6
February	45·5	68·5	11·8	61·3	75·8	97·4	5·8	50·5	75·4	40·3	139·9
March	28·4	59·8	31·1	24·1	25·5	92·6	17·8	8·6	15·8	41·7	11·6
April	51·9	49·6	38·8	9·6	22·6	29·4	0·0	13·9	0·4	0·6	15·9
Mean minimum air temperature, °C											
January	2·4	−1·3	3·5	3·9	3·2	2·1	−2·3	−2·1	−1·5	0·3	3·7
February	−0·6	1·0	1·7	1·6	4·2	4·0	−1·4	0·7	−0·3	0·1	2·8
Mean maximum air temperature, °C											
March	16·5	16·8	18·2	16·9	19·3	15·8	20·1	20·0	15·9	16·8	18·9
April	23·8	21·8	21·0	24·0	25·7	22·7	30·8	24·4	23·9	24·0	26·9
May	28·3	28·6	30·1	30·9	26·7	30·2	31·8	30·3	28·0	27·0	31·6

† Rainfall for separate months between September and December, rainfall for May, minimum air temperature for December and March to May, maximum air temperature December to February, have been omitted as their correlations with the feeding value of straw were weak (Table 4).
‡ Straw was not harvested in 1987 or 1991.

from January onwards, with standard deviations of *c.* 2 °C, but they were not strongly correlated with one another ($r = 0·34–0·55$). Rainfall was associated with increased *Tmin* in January and with reduced *Tmax* in March–May ($P < 0·05$ or $0·01$).

In addition to the relationships shown in Table 1, there were appreciable correlations between variables in some successive months. *Pptn*, *Tmax*, *Tmin* and *Frost* in January were highly correlated with their values in the following month ($r = 0·58$, 0·68, 0·69 and 0·73 respectively, $P < 0·05–0·001$). Similar but smaller correlations were seen between the meteorological variables of March and those of April ($r = 0·43$, 0·56, 0·40 and 0·08). Other correlations are apparent in the subset of annual data that was used for predicting straw feeding value (Table 2).

Straw feeding value indicators

Data for straw N, NDF and ADF were available for

Table 3. *A selection of barley straw feeding value indicators: annual least-squares means for all cultivars*

	Year ending											
	1982	1983	1984	1985†	1986	1988	1989†	1990†	1992	1993	1994	S.E.M.‡
Number of cultivars …	*2*	*3*	*8*	*9*	*4*	*9*	*8*	*6*	*5*	*6*	*4*¶	
Intake and digestibility of straw in vivo												
Voluntary DM intake (DMI), g/kg$^{0·75}$	45·7	35·8	48·4	48·8	39·4	31·6	76·6	54·0	29·6	N.M.	48·7	2·03
Digestible OM intake (DOMI), g/kg$^{0·75}$	19·4	13·8	20·3	19·8	18·9	13·6	45·7	N.M.	12·7	N.M.	22·4	1·06
Hohenheim in vitro *gas production test (HFT)*												
Asymptotic gas pool size, ml/0·2 g $(a+b)$	N.M.	N.M.	N.M.	46·3	44·9	42·4	63·8	61·0	43·9	N.M.	N.M.	1·27
Relative rate of gas production, h^{-1} (c)	N.M.	N.M.	N.M.	0·056	0·048	0·043	0·063	0·053	0·063	N.M.	N.M.	0·0017
DM loss in sacco												
Potential DM loss, g/kg DM $(a+b)$	N.M.	N.M.	N.M.	687	591	512	784	741	708	654	662	15·2
Relative rate of DM loss, h^{-1} (c)	N.M.	N.M.	N.M.	0·048	0·048	0·043	0·062	0·052	0·047	0·051	0·037	0·0038
Laboratory analyses of straw, g/kg DM												
Nitrogen	5·8	5·2	4·8	5·8	3·8	2·8	10·6	6·8	4·6	8·7	5·5	1·22
Neutral detergent fibre (NDF)	758	740	742	781	842	858	731	767	747	755	728	14·6
Acid detergent fibre (ADF)	432	467	419	435	514	527	358	403	430	421	400	8·2
Acid detergent lignin (ADL)	N.M.	N.M.	N.M.	51	73	72	35	44	48	67	58	5·8
DOMD *in vitro*	N.M.	N.M.	N.M.	433	419	387	606	560	458	486	N.M.	21·7
Average crop yields at the research farm, t/ha												
Straw yield	N.M.	1·37	1·99	4·63	5·09	N.M.	2·17	1·83	N.M.	4·59	3·88	*c.* 0·20
Grain yield	N.M.	2·28	2·03	3·06	4·13	4·11	N.M.	0·85	3·07	2·72	2·98	*c.* 0·14

† Straw was harvested by hand in 1985, 1989 and 1990 because plants were too short for combine harvesting.
‡ Root-mean-square average standard error of mean, calculated by SAS PROC GLM from cultivar × year interaction.
¶ Taken from a larger experiment with 32 genotypes.
N.M. Not measured.

Table 4. *Number of feeding value indicators† having significant* (P < 0·05) *correlations with potentially relevant monthly meteorological variables*

Month	Rainfall	Minimum temperature	Maximum temperature	Mean temperature	Frost events
Sept, Oct or Nov	0	N.C.	N.C.	N.C.	N.C.
December	0	0	0	0	0
January	3‡	2	0	0	3
February	6 (3)§	11 (4)	0	1	7 (1)
March	2	0	4	2	0
April	5 (2)	0	3 (1)	2	0
May	0	0	1	1	N.C.

† To avoid unwarranted counting of intercorrelated indicators, only 14 are considered here. They include all measurements described in the Materials and Methods section of the paper, except that observations of *in vitro* gas volume or *in sacco* DM loss were counted as one aggregate observation if correlations were significant ($P < 0{\cdot}05$) at most of the incubation times. *In sacco Lag* was excluded.
‡ Also straw yield ($P < 0{\cdot}05$).
§ The figure in parentheses is the number of correlations with $P < 0{\cdot}01$, if any were found.
N.C. Not calculated.

11 years, voluntary straw DM intake by sheep for 10 years, *in vivo* DOM intake and DOM in the DM for 9 years, *in sacco* DM loss and ADL for 8 years, *in vitro* digestibility for 7 years and *in vitro* gas production for 6 years (see Table 3). Coefficients of variation for these feeding value indicators ranged between 5% (NDF) and 39% (N), most of them being between 20 and 30%. In addition, straw yield was recorded in 8 years and grain yield in 9 years.

Some of the indicators (e.g. the results of *in sacco* DM loss or *in vitro* gas production at the various incubation times) add little information; a representative value of each was used in Table 4. *In sacco Lag* values did not vary significantly between years and have not been further analysed. The standard error of the mean (S.E.M.) shown in Table 3 is the root-mean-square average of annual values of S.E.M., which varied between 1·09 and 2·80 g/kg $BW^{0{\cdot}75}$ for DM intake and less widely for other data.

Bivariate correlation analysis

The number of feeding value indicators having significant ($P < 0{\cdot}05$ or 0·01) bivariate correlations with each monthly meteorological variable is shown in Table 4.

Between January and April, rainfall was negatively correlated with straw feeding value (intake, digestibility, *in sacco* DM loss, *in vitro* gas production and N) and positively correlated with cell wall constituents (NDF, ADF and ADL), in many instances reaching statistical significance (Table 5). Rainfall in at least one month in this period had effects (*P* usually $< 0{\cdot}05$ or $< 0{\cdot}01$) on all indicators of straw feeding value except for *in vivo* measurements (DM and DOM intakes), N and NDF (Table 5). Relationships with rainfall were, with two exceptions, strongest in February and March, the time of spikelet primordia development and stem elongation, and continued throughout April, the time of anthesis and commencement of grain-filling.

Tmin generally had effects on two indicators of straw feeding value in January and on nearly all indicators in February, with correlation coefficients having the same sign as those for rainfall. *Tmax* had effects between March and May, the period which included head emergence and grain-filling. In all cases, the higher the spring maximum temperature, the higher the feeding value of the straw.

Differences in responses of feeding value indicators to meteorological variables

The pattern of response to meteorological variables varied amongst feeding value indicators, a representative sample of which is shown in Table 5. Voluntary intakes of both DM and DOM had correlations ($P < 0{\cdot}05$) with *Tmax* in March and April. Cell wall constituents in straw DM (NDF, ADF, ADL) were correlated with *Tmin* in February and (to some extent) with rainfall in March or April. Indicators of rumen fermentability (*in vitro*, HFT, *in sacco*) and N were correlated with rainfall at some time between January and April, with *Tmin* in February, and with *Tmax* in March or April.

Selection of meteorological data to be used as independent variables in regression analysis

On the basis of Table 4, monthly rainfall from January to April inclusive, *Tmin* in January and February, and *Tmax* from March and May inclusive were included in the set of independent variables for multiple regression. The effect of autumn rainfall on

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Table 5. *Correlations between single monthly meteorological variables and a sample of feeding value indicators for barley straw*

Meterological variable	Abbreviation	Voluntary DMI	Voluntary DOMI	DOMD *in vitro*	HFT *a*+*b*†	HFT *c*†	*In sacco* *a*+*b*‡	*In sacco* *c*‡	Nitrogen	NDF	ADF	ADL
Number of years…		*10*	*9*	*7*	*6*	*6*	*8*	*8*	*11*	*11*	*11*	*8*
Rainfall, Sept to Dec§	*Pptn*(9–12)	0·08	0·24	0·06	0·03	0·25	0·00	0·36	0·08	0·24	0·02	−0·38
Rainfall, Jan	*Pptn*(1)	−0·32	−0·43	−0·83*	−0·79	−0·36	−0·43	−0·79*	−0·44	0·33	0·28	0·48
Rainfall, Feb	*Pptn*(2)	−0·55	−0·51	−0·89**	−0·89*	−0·66	−0·46	−0·97***	−0·57¶	0·27	0·41	0·51
Rainfall, Mar	*Pptn*(3)	−0·49	−0·43	−0·60	−0·52	−0·73	−0·83*	−0·28	−0·41	0·54	0·70*	0·63
Rainfall, Apr	*Pptn*(4)	−0·35	−0·45	−0·60	−0·46	−0·99***	−0·76*	−0·57	−0·49¶	0·10¶	0·41	0·64
Mean minimum °C, Jan	*Tmin*(1)	−0·22	−0·38	−0·81*	−0·70	−0·58	−0·57	−0·69	−0·50	0·33	0·35	0·65
Mean minimum °C, Feb	*Tmin*(2)	−0·48	−0·50	−0·79*	−0·66	−0·92**	−0·81*	−0·71*	−0·73*	0·71*	0·74**	0·80*
Mean maximum °C, Mar	*Tmax*(3)	0·74*	0·75*	0·71	0·81*	0·15	0·52	0·44	0·44	−0·18	−0·46	−0·40
Mean maximum °C, Apr	*Tmax*(4)	0·72*	0·82**	0·73	0·72	0·52	0·60	0·54	0·628*	−0·19	−0·50	−0·53
Mean maximum °C, May	*Tmax*(5)	0·64*	0·55	0·43	0·59	0·21	0·40	0·05	0·23	−0·27	−0·48	−0·56

† Based on 12 incubation times.
‡ Based on 5 incubation times.
§ There was, in addition to the results shown here, a significant negative correlation ($r = -0·76$, $P < 0·05$) between September rainfall and 72-h *in sacco* DM loss.
* $P < 0·05$; ** $P < 0·01$; *** $P < 0·001$.
¶ When these correlations were computed for the same 8 years as the *in sacco* results, they reached significance ($P < 0·05$).

straw feeding value was weak (Tables 4 and 5), but because rainfall in all months between October and March can have significant and positive correlations with grain yield (van Oosterom *et al*. 1993), total rainfall between September and December was also included as an independent variable.

The set of independent variables actually used in the calculation of regression equations comprised the ten meteorological variables described above and all possible time-sequences of them. The sequences were: total *Pptn* in months 9–1 (i.e. September to the following January), 9–2, 9–3, 9–4, 1–2, 1–3, 1–4, 2–3, 2–4, 4–5; average *Tmin* in months 1–2; and average *Tmax* in months 3–4, 3–5, 4–5.

Other meteorological variables (mean temperature and *Frost*) were discarded for subsequent analyses because they had weaker correlations with feeding value indicators than the meteorological variables already selected, with which they were closely correlated.

Bivariate regression equations

The best-fitting bivariate regression equations are shown in Table 6*a*, and closely mirror the pattern of correlation shown in Table 3. Aggregation of *Pptn* and *Tmax* into time-sequences improved levels of significance appreciably.

Multiple regression analysis

Multiple regression analysis for annual mean feeding value indicators is shown in Table 6*b*. The meteorological variable accounting for the larger share of the variation in each equation is stated first. Only those regression equations whose residual standard errors were no smaller than the standard errors of measurement are normally shown, to exclude obviously overdetermined equations.

Results clarified the separate effects of *Pptn*, *Tmin* and *Tmax* described above. *Tmax* in the March–May period, followed by *Pptn* in February, predicted voluntary DM and DOM intake, and *Pptn* was followed by *Tmax* for predicting *in sacco* DM loss, *in vitro* DOMD and N. In addition to the bivariate relationship between cell wall constituents and *Tmin* (Tables 5 and 6*a*), *Tmax* and (for NDF) autumn *Pptn* were selected by PROC REG. Where ADF was expressed as a proportion of NDF and ADL as a proportion of ADF, *Pptn* rather than *Tmin* was selected (see Discussion).

Responses of different types of barley to meteorological variables

Multiple regression analyses for five types of barley straw (Table 7) are shown in Table 8. Just as for the mean voluntary intake over all cultivars, voluntary intake of each of the five types was more strongly affected by *Tmax* in March–May than by *Pptn*, except

Table 6. *Best-fitting* (a) *bivariate regression equations and* (b) *multiple regression equations for predicting annual means of selected feeding value indicators for barley straw. Numbers in parentheses following independent variables refer to months*; *units are as in Table 3*

(*a*)	
Voluntary DMI = −125 + 7·1 Tmax(3–5)**†	$S_{y.x}$‡ = 7·1, 8 D.F.
Voluntary DOMI = −48·5 + 2·82 Tmax(3–5)**	$S_{y.x}$ = 2·57, 7 D.F.
HFT *a*+*b* = 66·8 − 0·131 Pptn(1–2)*	$S_{y.x}$ = 4·21, 4 D.F.
HFT *c* = 0·063 − 0·00068 Pptn(4)***	$S_{y.x}$ = 0·0006, 4 D.F.
In sacco a+*b* = 764 − 2·25 Pptn(3–4)**	$S_{y.x}$ = 40·2, 6 D.F.
In sacco c = 0·060 − 0·00017 Pptn(2)***	$S_{y.x}$ = 0·0019, 6 D.F.
Nitrogen = 9·6 − 0·021 Pptn(1–4)**	$S_{y.x}$ = 1·55, 9 D.F.
NDF = 747 + 16·9 Tmin(2)*	$S_{y.x}$ = 32·1, 9 D.F.
ADF = 412 + 19·9 Tmin(2)**	$S_{y.x}$ = 35·1, 9 D.F.
ADL = 48 + 5·4 Tmin(2)*	$S_{y.x}$ = 9·0, 6 D.F.
DOMD *in vitro* = 625 − 0·96 Pptn(1–3)***	$S_{y.x}$ = 26·0, 5 D.F.
Straw yield = 0·0137 Pptn(9–12)***	$S_{y.x}$ = 1·207, 7 D.F.
Straw yield = 1·62 + 0·0264 Pptn(1)*	$S_{y.x}$ = 1·076, 6 D.F.
Grain yield = 0·0094 Pptn(9–3)***	$S_{y.x}$ = 0·755, 8 D.F.
Grain yield = 0·90 + 0·0111 Pptn(1–3)*	$S_{y.x}$ = 0·752, 7 D.F.
(*b*)	
Voluntary DMI = −104 + 6·6 Tmax(3–5)*** − 0·15 Pptn(2)**	$S_{y.x}$ = 3·5, 7 D.F.***
Voluntary DOMI = −35·1 + 2·42 Tmax(3–5)*** − 0·040 Pptn(2–3)*	$S_{y.x}$ = 1·55, 6 D.F.***
In sacco a+*b* = 344 − 2·19 Pptn(3–4)** + 14·1 Tmax(5)*	$S_{y.x}$ = 28·0, 5 D.F.**
In sacco c = 0·041 − 0·00016 Pptn(2)*** + 0·00084 Tmax(3–4)**	$S_{y.x}$ = 0·0009, 5 D.F.***
Nitrogen = 0·4 − 0·017 Pptn(1–4)* + 0·34 Tmax(4)$^{P=0·079}$	$S_{y.x}$ = 1·34, 8 D.F.**
NDF = 954 + 20·4 Tmin(2)** − 0·64 Pptn(9–12)** − 10·0 Tmax(5)*	$S_{y.x}$ = 19·4, 7 D.F.**
ADF = 774 + 17·8 Tmin(2)** − 15·1 Tmax(3–5)*	$S_{y.x}$ = 25·6, 8 D.F.**
ADL = 140 + 5·0 Tmin(2)** − 3·1 Tmax(5)$^{P=0·054}$	$S_{y.x}$ = 6·6, 5 D.F.*
DOMD *in vitro* = 324 − 0·91 Pptn(1–3)*** + 10·0 Tmax(5)*	$S_{y.x}$ = 15·9, 4 D.F.***
Straw yield = 12·1 + 0·028 Pptn(1)* − 0·36 Tmax(5)$^{P=0·076}$	$S_{y.x}$ = 0·83, 5 D.F.*
Grain yield = 10·7 + 0·014 Pptn(1–3)** − 0·35 Tmax(5)*	$S_{y.x}$ = 0·47, 6 D.F.**
Grain yield = 11·1 + 0·008 Pptn(9–3)*** − 0·38 Tmax(5)*** + 0·29 Tmin(12)**	$S_{y.x}$ = 0·21, 5 D.F.***

† Figures in parentheses denote beginning and end months of a period: for example, Tmax(3–5) denotes mean maximum temperature for the months March, April and May; Pptn(9–3) denotes the total rainfall in September to the following March.
‡ $S_{y.x}$ = Mean square residual standard error, followed by error D.F. and significance of multiple correlation.
* $P < 0·05$; ** $P < 0·01$; *** $P < 0·001$.
HFT *in vitro* gas production results were not analysed in (*b*) because of insufficient degrees of freedom.

in the case of the early-maturing 6-row cultivar Beecher. The coefficient for *Tmax* varied to a relatively lesser extent among the other four types (between 5·7 and 7·2 g/kg$^{0·75}$ for each °C when *Pptn* has been accounted for). There were, however, differences in the partial responses of the types to February rainfall: the coefficient increased from non-significant with black-seeded 2-row landrace selections through −0·11 with white-seeded 2-row landrace selections to between −0·18 and −0·21 for exotic 2-row and 6-row cultivars.

Effects of meteorological variables on straw and grain yield

Rainfall early in the growing season affected straw and grain yield; additionally cold and heat stresses affected grain yield (Table 6).

Consistency of measurement of feeding value indicators

The voluntary intake and digestibility of 1992 straw were as low as in 1988 straw, despite other feeding value indicators having close to average values (Table 3). The low intake of 1992 straw was substantiated by sheep preference data (see Discussion).

It must be admitted that different indicators of straw quality were measured in different subsets of the 11 years (Table 3). One would expect correlation analysis to give somewhat different results according to the subset of years used. This phenomenon affected statistical inferences only for N and to some extent for NDF; the pattern of bivariate correlation varied according to whether 8 or 11 years' data were used (Table 5). On the other hand, bivariate regression over the 11 years using time-sequences of *Pptn*

Table 7. *Annual values for voluntary DM intake for each of five types of barley straw, g/(kg body weight)$^{0.75}$*†

	Year ending										
Type of barley	1982	1983	1984	1985	1986	1988	1989	1990	1992	1994	mean (S.E.)‡
Black-seeded 2-row landrace selections (*Arabi aswad, Tadmor and Zanbaka*)	N.M.	N.M.	N.M.	49·5	N.M.	34·7	66·7	48·9	28·8	55·4	45·1 (1·25)
White-seeded 2-row landrace selections (*Arabi abiad* and *Arta*)	46·8	40·6	53·1	47·2	43·9	36·0	74·0	55·7	36·2	52·8	50·5 (0·91)
All 2-row exotic cultivars (*ER/Apam* and *WI2291*)	N.M.	34·7	49·5	45·5	39·8	33·0	77·0	N.M.	35·8	N.M.	46·5 (1·19)
Early maturing 6-row exotic cultivar (*Beecher*)	42·8	28·7	42·7	40·3	35·2	24·1	74·7	N.M.	N.M.	N.M.	40·5 (1·11)
Medium maturing 6-row exotic cultivars (*Arar*, *Badia*, *C-63* and *Rihane*)	N.M.	N.M.	46·6	47·5	37·0	28·0	81·2	49·9	31·7	40·6	45·1 (0·87)

† A sixth type of barley, late maturing 6-row exotic cultivars (represented by *Antares*), has been omitted because data were available in only 5 years.
‡ Least squares mean for all years, with its standard error in parentheses.
N.M. Not measured.

Table 8. *Best-fitting bivariate and multiple regression equations for predicting voluntary intake for each of five types of barley straw, g/(kg body weight)$^{0.75}$*

Black-seeded 2-row landrace selections	
DMI = −126+7·1 Tmax(3–5)**	$S_{y.x}$ = 1·71, 4 D.F.
White-seeded 2-row landrace selections	
DMI = −103+6·3 Tmax(3–5)***	$S_{y.x}$ = 1·80, 9 D.F.
DMI = −93+6·1 Tmax(3–5)*** −0·10 Pptn(2)*	$S_{y.x}$ = 0·90, 8 D.F.***
All 2-row exotic cultivars	
DMI = −147+8·1 Tmax(3–5)**	$S_{y.x}$ = 2·17, 5 D.F.
DMI = −80+5·7 Tmax(3–5)*** −0·19 Pptn(2)***	$S_{y.x}$ = 0·52, 4 D.F.***
Early maturing 6-row exotic cultivar (Beecher)	
DMI = 73−0·18 Pptn(1–4)**	$S_{y.x}$ = 2·85, 5 D.F.
DMI = −41−0·12 Pptn(1–4)** +0·9 Tmax(4–5)*	$S_{y.x}$ = 1·35, 4 D.F.**
Medium maturing 6-row exotic cultivars	
DMI = −152+8·1 Tmax(3–5)*	$S_{y.x}$ = 3·48, 6 D.F.
DMI = −116+7·2 Tmax(3–5)*** −0·20 Pptn(2)***	$S_{y.x}$ = 0·94, 5 D.F.***

† $S_{y.x}$ = Mean square residual standard error, followed by error D.F. and, for multiple regression, significance of multiple correlation.
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

revealed its importance in determining straw N content (Table 6*a*). The complexity of meteorological effects on NDF is illustrated by the multiple regression equation of Table 6*b*.

DISCUSSION

Effects of meteorological variables on straw feeding value and grain yield

The results show that barley straw feeding value can be increased by moisture stress, cold stress and heat stress during crop growth in Mediterranean environments. Rainfall between January and April may reduce the feeding value of straw by two mechanisms: by increasing the size and thereby the mechanical strength and resistance to digestion of stems, then later by aiding the translocation of soluble nutrients into the seed head, thereby reducing their concentration in the straw. The latter effect is offset where maximum temperatures are high enough to disrupt the translocation of nutrients. Low mean minimum temperature in February (associated with frost) reduces NDF content (i.e. increases the content of neutral detergent solubles), perhaps incidentally to a reported decrease in grain yield (van Oosterom *et al.* 1993; Table 6*b*), although other mechanisms may be involved.

In general, stress conditions that decrease grain yield also increase the feeding value of straw, with stresses occurring early in the growing season having greater effects on grain yield and stresses occurring later having greater effects on straw feeding value. For example, rainfall before January was rarely associated with feeding value (Table 6*b*), but has been shown to increase grain yield (van Oosterom *et al.* 1993; Table 6*a*). This was expected, because immature plants are able to adjust the number of tillers rather precisely in response to soil moisture, thus buffering the effects of early rainfall on tiller morphology (Evans & Wardlaw 1976; data of Thomson *et al.* 1993). As plants mature and progressively lose their options for responding to the environment, stress is increasingly likely to affect the size, morphology and retention of assimilate in tillers.

Effects of rainfall

There was no significant effect of rainfall up to and including December, the time of seedling emergence, on straw feeding value indicators, other than the weak negative correlation between September rainfall and 72-h *in sacco* DM loss (Table 5) and its appearance (with a *negative* coefficient) in the multiple regression equation predicting NDF (Table 6*b*). This contrasts with the results of van Oosterom *et al.* (1993) for 18 year × site combinations in northern Syria, in which rainfall in December accounted for 47–49% of the variance in barley grain yield in multiple correlation analysis, and two of our equations predicting grain yield (Table 6).

Later in the growing season, from January to as late as April, rainfall reduces straw feeding value, particularly affecting digestion in rumen fluid (gas production, *in sacco* DM loss or *in vitro* DMD) and N. In contrast, van Oosterom *et al.* (1993) found that rainfall in February made no significant contribution to prediction of grain yield by multiple regression, and that rainfall in March or April was not significantly correlated with grain yield.

The effects of moisture stress on barley straw feeding value from January onwards broadly resemble its effects on pasture grasses, in which the concentration of soluble carbohydrates and N are generally increased, and cell wall and lignin content reduced (Wilson 1982).

An earlier study at ICARDA estimated the effect on straw feeding value of the application of up to 250 mm of supplementary water during the growing season (Thomson *et al.* 1993). Each millimetre of supplementary irrigation reduced the 48-h *in sacco* DM loss of straw by 0·70 g/kg. In the present study (Table 6), each millimetre of rain in February–April reduced the 48-h *in sacco* DM loss by 1·53 g/kg, whereas rain during early growth of the crop had no significant effect. In the report of Thomson *et al.* (1993) supplementary irrigation increased the number as well as the mass of individual tillers, effects usually associated with rain during early growth (Evans & Wardlaw 1976).

Thomson *et al.* (1993) describe other effects of supplementary irrigation on morphological features, such as an increase in stem height and decrease in leafiness of the straw. These features are associated with a decrease in the voluntary intake and digestibility of straw (Capper 1988).

The present set of data represent the drier end of the range of environments in which barley is grown. The very dry spring of 1989 – from January onwards rainfall was 17% of the 16-year mean – exerted its extreme effect on straw quality largely by retarding the growth of barley before anthesis, with observable reductions in grain and straw yield (Table 3), plant height, number of seeds per tiller, and weight per seed; the leaf:stem ratio was increased. At the wetter end of the range of environments, the marginal effect of extra rainfall on feeding value may be smaller than that found here, as was reported for the *in vitro* digestibility of wheat by Purser (1982). Where rain occurs after anthesis, new tillers may grow, leading to an increased palatability and N content of the straw (A. Chriyaa & A. Amri, unpublished).

The weak response of straw nitrogen to meteorological variables

Spring rainfall consistently reduced straw N (Tables 5 and 6), but the significance of correlations with individual months' rainfall was weak. Fertilizer application was minimal, so that wet growing conditions may have initially favoured mineralization of soil N, then later have caused dilution of N if plant biomass was increased. The N content of straw would also have reflected the concentration of N in the soil at sowing time. If one assumes that the concentration of N in grain was 1·8 g/kg DM, between 40 and 80 kg N were removed per ha (Table 3), a quantity comparable to the amount of N fertilizer applied. Variation in straw N content due to fertilizer application may not have had a large impact on other indicators of straw feeding value; for example, N fertilization can simultaneously increase the digestibility of leaf and decrease the digestibility of stem (Kernan *et al.* 1984).

The weak effect of spring mean maximum temperatures on straw N concentration was expected, because high maximum temperatures at grain-filling affect N uptake by seeds less than they affect carbohydrate uptake (Evans & Wardlaw 1976).

Effects of temperature

Low mean minimum temperature in February decreased the NDF content of straw, and reduced ADF and ADL as proportions of the DM (Table 6). The ratios of ADF:NDF and of ADL:ADF were not correlated with minimum temperature, but were correlated primarily with rainfall (not shown). Decreased NDF content might be better expressed as an increased content of cell solubles, possibly accompanying a reduction of grain yield by frost as observed by van Oosterom *et al.* (1993) and in the present study (Table 6*b*).

It was also possible that temperature was directly affecting cell wall composition. Our findings parallel the results of Wilson *et al.* (1991) in which lignin content decreased with decreasing air temperature in temperate and tropical Graminaceae. Part, but not all, of the effect of cold conditions in lowering the cell wall content of Graminaceae may also be mediated by a reduction in tiller size (Deinum 1966, 1981; Wilson 1982). Loss of leaves due to frost (Loss & Siddique 1994) did not appear to be important, as the effect of decreased leafiness on the feeding value of straw would be the reverse of that found here.

Mean maximum temperature (*Tmax*) in March, April and May had positive partial effects on straw feeding value (Table 6*b*). Temperatures > 30 °C affect grain yield by shortening the *period* of grain-filling without a fully compensating increase in the *rate* of grain-filling, and are common in Mediterranean areas (Evans & Wardlaw 1976; Loss & Siddique 1994). In the present study an effect on grain-filling would have begun to operate in mid-April. More severe heat stress, even on one or two days, may lead to the formation of a heat shock protein which interrupts the transfer of assimilate to the grain (J. M. Peacock, personal communication). Heat stress would be expected to affect straw feeding value by increasing assimilate concentrations in straw, detectable in the present study as a reduction in NDF and a small increase in N (Tables 5 and 6*b*).

The inclusion of March *Tmax* in prediction equations may reflect the association of high *Tmax* with low rainfall (Table 1). High *Tmax* in March occurred in the drought years 1989 and 1990 (Table 2), and was correlated with a small number of feeding value indicators (Tables 5 and 6). The warm, sunny conditions associated with high *Tmax* also contribute to the onset of drought stress by increasing evapotranspiration (Loss & Siddique 1994).

In Mediterranean climates, rain-fed cereals are planted at the coldest time of the year and mature in hot, dry conditions (Loss & Siddique 1994). The frequency of maximum temperature in equations for predicting straw feeding value indicators (Table 6*b*) contrasts with the finding of van Oosterom *et al.* (1993) that *Frost* was the most important variable after rainfall affecting grain yield.

Feeding value indicators that were most affected by mean maximum temperature

The effect of *Tmax* in spring on voluntary intake was more pronounced than it was on other feeding value indicators (Tables 5, 6 and 8). In particular, the intake of straw harvested in 1992 (the year with the lowest spring maximum air temperatures) was lower than might be predicted from other feeding value indicators. This may be illustrated using data for straws harvested in 1992, 1985 and 1988. Their respective voluntary DM intakes were 29·6, 48·8 and 31·6 g/kg$^{0\cdot75}$ (1992 resembling 1988), whereas their *in sacco* $a+b$ measurements were 708, 687 and 512 g/kg (1992 resembling 1985). Other indicators shown in Table 3 tell the same story. To test whether the discrepancy was related to sheep behaviour, data from a pair-comparison trial with the straws (Goodchild *et al.* 1995) was examined. The least-squares mean refusals in paired comparisons were 21, 2 and 26 g for 1992, 1985 and 1988 straws, suggesting that the low intake of 1992 straw was associated with its acceptability to sheep rather than its digestive characteristics.

Genotype × environment interactions in the feeding value of straw

The existence of a genotype × environment interaction has for many years discouraged breeders from selecting barley for the genotypic feeding value of its straw (Capper *et al.* 1988). Given that cold, drought and heat stresses affect straw feeding value and grain yield in opposite directions, genotypes in which the feeding value of straw is most enhanced by stress are likely to be those in which the yield of grain is most reduced under stress.

The partial effects of rainfall on the voluntary intake of straw varied by type of barley (Table 8). The meteorological extremes in 1988 and 1989 affected the intake of all types of barley straw. Although the intake of 2-row cultivars in 1988 was higher than that of 6-row cultivars (*c.* 35 *v. c.* 26 g/kg $W^{0\cdot75}$), the ranking in 1989 was reversed (*c.* 70 *v. c.* 78 g/kg $W^{0\cdot75}$). Looked at another way, the intake of the two types of 6-row cultivars was the most affected by year (3·1 or 2·9-fold) and the intake of black or white-seeded 2-row landrace selections the least (1·9 or 2·1-fold). The intake of 2-row exotic varieties was affected to an intermediate extent (2·3-fold). Capper *et al.* (1988) report a similar reversal of ranking between wet and dry sites amongst three types of barley in 1986.

Selection strategies for barley straw feeding value

Two questions that arise are, *which* type of barley is the most desirable and *how* does one identify it? Stability in grain yield between years is a desirable goal in environments where drought and heat stress are common (Ceccarelli 1993). It so happens that the types of barley that have the most stable grain and straw yields (2-row landraces and selections from them) also had the most stable voluntary straw intakes across years (Table 7). It may be said with confidence that straw *feeding value* is more important than straw yield in favourable growing seasons, whereas straw *yield* is more important than straw feeding value when the season is poor. The high yield of straw and generally low voluntary intake in favourable years can be offset by storing the straw for use in drought years; cultivars with straw having the highest feeding value are the most likely to be stored. Therefore the feeding value of straw grown in favourable years is the trait that should be genetically selected for.

Although breeding for drought-tolerant genotypes needs to take place under stress conditions (Ceccarelli 1993), the criterion used for selection for feeding value should predict the ranking of straw grown under *favourable* conditions. It is beyond the scope of this paper to identify suitable criteria, but preliminary findings at ICARDA suggest that the degradability of cell wall (and related criteria) of genotypes is more stable across years than the concentration of cell contents or nitrogen. This is known to hold true in crops grown in Europe, for example barley (Wright & Hughes 1991) and maize harvested at silage maturity (Deinum 1988). Indicators of feeding value must also accurately rank straws according to the performance of the animals consuming them.

Predicting the effects of meteorological variables in other regions

The effect of the environment in temperate latitudes is broadly similar to current findings. In England and Wales, the feeding value of barley straw harvested in varietal trials in 1987 varied according to location; feeding value was highest (high *in sacco* and *in vitro* digestibility, low NDF, ADF and lignin) at one site in the warm southwest, and lowest at three sites in the west and north, which tended to be the wettest and coldest. Four sites in the drier east and south were intermediate (Wright & Hughes 1991). In the American Midwest, irrigation which roughly doubled barley yields significantly reduced *in vitro* digestibility and hemicellulose in straw, and increased ash, NDF, ADF and lignin (Erickson *et al*. 1982). In both of these reports, location (within year) did not significantly affect the crude protein content of straw.

Extrapolation of the best-fitting prediction equations for straw feeding value (Table 6) to regions outside the study area resulted in impossible negative or large positive values for feeding value indicators (not shown), indicating that the equations were highly site-specific. Equations were most site-specific where temperature, in particular *Tmax*, was one of the independent variables. Heat stress at the study site can be caused by one or more days of exceptionally high maximum temperature, which in the current data set would have been recorded as a relatively smaller elevation of *Tmax*, the mean maximum temperature. As a result of the infrequency of very hot days, the computed regression coefficients of *Tmax* were too large to be accurately applied at sites with generally higher maximum temperatures. *Absolute maximum temperature* or *number of days with maxima* > 30 °C (Loss & Siddique 1994) are less site-specific indicators of heat stress, but such data are rarely tabulated. Furthermore, the effect of high temperatures in any particular month will depend on the stage of physiological development that the plant has reached, which will itself be site- and cultivar-specific.

In Mediterranean farming systems, crop yields depend among other things upon a choice of planting date and cultivar that minimizes the probability of cold and heat stresses (van Oosterom & Acevedo 1992). Therefore, any model designed to predict the effects of these stresses on straw feeding value must allow for actual practice in sowing and harvesting dates and for cultivar growth patterns. Genotypes vary in their susceptibility to thermal stress; in the Mediterranean, winter growth or vernalization requirement may mitigate the effects of cold stress, and earliness of maturity may allow escape from heat stress (van Oosterom & Acevedo 1992). Modelling heat stress also requires knowledge of absolute maximum temperatures. Therefore, prediction equations for straw feeding value need *either* to be calibrated for each locality *or* to include information on planting dates, absolute maximum temperatures and the growth patterns of locally-used cultivars.

Effects of meteorological conditions on the farm economy

Straws harvested in 1988, 1989 and 1992 provide examples of the effect of environment on the feeding value of straw in the diet of sheep. In 1989 (hot, dry spring) feeding value was high (Table 3); sheep consumed 46 g digestible OM per unit metabolic body size (kg $BW^{0·75}$), sufficient energy for a sedentary 50-kg ewe to produce 0·8 kg milk a day (AFRC 1993). In contrast, the straw yield was about half of what was expected in an average year. Its crude protein ($N \times 6·25$) content was 66 g/kg DM, about half of what is required for producing 0·8 kg milk a day. In 1988 (cold, wet spring) and 1992 (cold winter and spring) the voluntary intake of digestible OM was 13 g/kg $BW^{0·75}$, only *c*. 0·6 of maintenance needs (AFRC 1993). Once again the straw contained insufficient crude protein (18 or 29 g/kg DM). The yield of straw was high, particularly in relation to its voluntary intake (Table 3).

Therefore, in all years, some N-rich supplementary feed (part of which may be non-protein N) needs to be fed with barley straw. In dry years, barley straw may to some extent be replaced with wheat straw, the feeding value of which is also increased by low rainfall (Purser 1982); but in many countries and years any straw ceases to be readily available before the grazing season commences. The often inadequate total quantity of straws and other locally-produced feeds in Middle Eastern countries has recently been supplemented with imported cereals because they have been a relatively cheap source of metabolizable energy. If they are fed with the current year's straw in a dry year, the resulting low-fibre ration will tend to depress milk fat production in lactating sheep (El Awad *et al*. 1995). A rational alternative would be to preserve some of the straw produced in wet years for feeding in dry years; this is in fact practised in some countries including Morocco and Tunisia. Selection by breeders of genotypes that have high feeding value in wet years would yield easily appreciated benefits.

Conclusion

The effect of meteorological conditions on straw feeding value is the end product of at least four processes: first, autumn and early winter rainfall increases the number of tillers in which the crop invests, affecting the potential grain yield rather than tiller size or straw feeding value. Second, winter and early spring rainfall increases the height and robustness of plants, facilitates crop development and helps to prevent retention of assimilates in the straw due to terminal stress; these factors taken together reduce the feeding value of the straw. Third, warm minimum temperatures in winter prevent adverse effects of cold stress on grain yield and have negative effects on straw feeding value, possibly by more than one mechanism. Fourth, high maximum temperatures during grain-filling reduce grain yield and increase the retention of assimilates in the straw; they also have an indirect influence by decreasing soil water storage through evapotranspiration. High monthly mean maximum temperatures do not fully reveal occasional days of extremely high maximum temperature leading to heat stress, which can abruptly curtail the translocation of assimilates into the grain. In addition to these mechanisms, severe early drought stress results in cessation of plant growth in a relatively immature, leafy and barren state.

Simple models predicting the influence of meteorological variables on the production and nutritive value of barley straw are tools which could help farmers and feedingstuff importers to plan adequate and balanced sheep diets. Models developed from the data of the present paper are relevant to the location and cultivars used, and would need to be recalibrated for use in other regions.

The numerous mechanisms by which environment can affect the feeding value of straw also affect the yield of grain and straw, and can throw light on important genotype × environment interactions. The lack of published information on these mechanisms and their potential impact on straw utilization imply that further studies of the effect of diverse environments on the feeding value of straw are needed.

Understanding how various indicators of feeding value are genetically correlated with grain yield, how they are affected by genotype × environment interaction, and how precisely they can be used to predict animal performance, will facilitate the genetic selection of straw for improved feeding value.

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