Yield and protein concentration of spring malting barley: the effects of cropping systems in the Paris Basin (France)

Marianne Le Bail, Jean-Marc Meynard

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Original article

Yield and protein concentration of spring malting barley: the effects of cropping systems in the Paris Basin (France)

Marianne Le BAIL[a]*, Jean-Marc MEYNARD[b]

[a] Institut National Agronomique Paris-Grignon, Département AGER, UMR SAD-APT, 16 rue Claude Bernard, 75231 Paris Cedex 05, France
[b] Institut National de la Recherche Agronomique, UMR d'Agronomie INRA INA P-G, BP 01, 78850 Thiverval-Grignon, France

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Abstract – In an intensive farming region, where farmers achieve very good results with winter wheat or sugar beet, there are still many problems in achieving combined control of yield and grain protein concentration in spring malting barley. A regional agronomic diagnosis was performed on the variations of both these outputs, in a network of twenty farmers' fields for three years. Three key variables explained the joint variations in yield and protein concentration: total nitrogen absorbed by the crop, the efficiency of absorbed N relative to the number of grains, and mean grain weight. Analysis of variations for these variables, within the network, enabled us to understand which situations produced satisfactory results and which did not: available nitrogen in the soil, topsoil structure, crop water supply and the level of the root disease take-all, were the main environmental conditions affecting yield and grain protein concentration. Improvements in cropping systems and barley husbandry are proposed in order to increase yield and manage protein concentration.

grain nitrogen concentration / spring barley / topsoil structure / agronomic diagnosis / take-all / cropping systems

Résumé – Rendement et taux de protéines de l'orge de printemps brassicole : effet des systèmes de culture dans le bassin parisien (France). Dans une région de culture intensive, où les agriculteurs ont de très bons résultats en blé et betterave sucrière, ils rencontrent quelques problèmes pour maîtriser à la fois le rendement et le taux de protéines de l'orge de printemps destinée à la brasserie. Un diagnostic régional a été réalisé sur les variations de ces deux composantes à partir de réseaux de parcelles agricoles (une vingtaine chaque année pendant trois ans). Trois composantes clés expliquent ces variations : l'azote absorbé par la culture, l'efficience de l'azote pour le nombre de grains et le poids moyen des grains. L'analyse de ces composantes permet de comprendre les situations dans lesquelles les performances de la culture sont plus ou moins satisfaisantes : l'azote disponible dans le sol, l'état structural de celui-ci, l'alimentation hydrique et les attaques racinaires de piétin échaudage sont les principales conditions qui affectent les performances de la culture. Des améliorations des systèmes de culture sont proposées en vue de maîtriser à la fois les niveaux du rendement et du taux de protéines.

taux de protéines / orge de printemps / structure du sol / diagnostic agronomique / piétin échaudage / système de culture

1. INTRODUCTION

Two thirds of barley purchased by French maltsters are spring sown varieties [27]. However, the area sown with spring barley in France decreased significantly in the 1970s and 80s, mainly because it provided lower and more irregular yields than winter cereals or maize. However, in the last ten years, maltsters have sought to increase spring barley production in regions near their processing facilities (the north and east of France). This coincided with the cereal growers' desire to find lucrative production opportunities to compensate for falling wheat and maize prices. Production contracts were drawn up between farmers and grain collecting firms, to provide the maltsters with a steady supply of adequate quality grain. The contract stipulates the variety to be grown, and the grain is paid for according to its quality in terms of grain plumpness, which closely correlates with mean weight per grain and grain protein concentration. Optimum grain protein concentration is 10% of the dry weight and the maximum allowed is 11.5%.

For malting barley to be grown more widely, it must be profitable for the farmers. They must regularly obtain high

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* Correspondence and reprints
lebail@inapg.inra.fr

Table I. Soils and crop sequences for the network of farmers' fields.

	Luvisol developed on loess deposits	Cambisol or Luvisol on sandy sediments or Fluvisol on sandy alluvium	Gleyic Luvisol or Vertisol on clayey sediments	Rendzina on limestone	All
Cereals: straw buried*	14	5	4	4	27
Cereals: straw harvested*	7	6	2	1	16
Cereals with farm manure**	3	1	1		5
Corn*	2	3		1	6
Sugar beet*	4	4	1		9
High-protein plants*	1				1
Grassland			1		1
All	31	19	9	6	65

Number of fields (three years joined). Empty space: situations we did not meet in the area.
* No livestock manure during the last three years.
** Livestock manure less than three years ago.

yields and satisfactory protein levels. But, as many authors point out, the relationship between these two characteristics is complex.

An analysis [50] of one hundred experiments on six species (including wheat and barley) published between 1938 and 1990 concludes that, comparing different genotypes, once the "noise" due to environmental factors has been eliminated, there is an inverse relation between yield and grain protein concentration. However, environmental factors have more effect than variety choice on both yield and grain protein [29, 48]. Experiments studying the impact of environmental factors generally test different sowing dates, sowing densities, nitrogen input levels and amounts of available water. With spring barley, late sowing reduces yield and increases protein concentration [60]. This effect of late sowing is attributed to water stress: irrigation removes this limiting factor and improves both yield and grain protein [31, 60]. Increasing the nitrogen application rate generally increases yield and grain protein concentration in linear or quadratic fashion depending on the initial level of nitrogen in the soil (spring barley: [11, 58]; wheat: [4]). In some situations, with the highest N application rates, yield may fall while grain protein concentration continues to increase [4]. In fact, it is difficult to control both these parameters at the same time, as this requires a precise control of N and water supply, sowing, etc. To identify targets for research and development, make manufacturers' specifications more precise and propose coherent crop management systems, one must identify those cropping systems and environmental factors that contribute most to combined high yield and high grain quality.

In this article we present the results of a study designed to rank the causes of variation in yield and grain protein concentration of spring barley in an area in the north-eastern Paris Basin, France. The research was supported by a malting group and a group of cereal collecting firms; its purpose was to identify techniques for barley crop management and for the characteristics of fields to be sown, so as to control yield and grain quality together.

2. MATERIALS AND METHODS

2.1. The region and the network of farmers' fields

A three-year network of farmers' fields was set up, in eastern Picardie, roughly sixty kilometres north-east of Paris. Using the diagnostic method for assessing regional variations in crop results [6, 18, 40], the sample of fields (20 to 30 fields each year) were chosen as being representative of environmental and crop management variations in the region (Tab. I).

The region (70 km north to south, 40 km east to west) lies in the Paris sedimentary basin. Its southern part is fairly uniform (luvisols developed on loess deposits). To the north, the loess deposits are thinner and overlie a varied tertiary era substrate that includes sandy and clayey sediments and limestone: luvisols that have formed on loess or sandy sediments are predominant, but there are also gleyic luvisols and vertisols on clayey sediments, from which excess water drains slowly. On the edges of the plateau there are rendzinas on limestone. The Oise valley runs through the region and its predominant soil type is sandy alluvium [3].

Climatic variations within the region are slight and they do not constitute a sampling criterion. The climate is temperate maritime with some continental influences. Mean monthly temperatures range from 4–5 ^{o}C in January to 17 ^{o}C in July. Precipitation is fairly well distributed through the year, at 50–70 mm per month.

Barley in this region is usually preceded by another cereal. In most cases the stubble is ploughed in and no livestock manure is applied, but in order to vary the amount of N supplied by the soils in our sample, we included a few fields where the straw was exported and others where manure had been applied within the preceding three years. We also included some fields where the preceding crops were not cereals but sugar beet, protein crops or maize.

Furthermore, because of the pace of change in varieties grown in the region, we had to change from Pression, the variety grown in the 1989 field network, to Volga for the 1990 and 1991 networks. However, variety comparison trials that

Table II. Yield and protein rate components for the genotypes Pression and Volga in three trials in Picardie (1990-1991) [32].

	VOLGA		PRESSION		Paired-sample comparison*
	Mean	Standard deviation	Mean	Standard deviation	
NG – Number of Grains (/m^2)	12824	4163	12224	3302	0
W1G – Grain Weight (mg)	39.8	4.3	41.6	2.8	0
TOT N – total N absorbed (kg·ha^{-1})	149.7	53.8	161.3	55.2	0
EFF – N efficiency relative to NG (grains·g^{-1})	901.9	223.4	811.0	189.1	≠ 0
NHI – N Harvest Index	0.60	0.047	0.59	0.042	0

* T-test of the null hypothesis of the mean [Volga-Pression] (for a 95% confidence level).

were being run at the same time in the same region showed that the two varieties are very similar with regard to yield components (Tab. II) [32]. Only the ratio of the number of grains to the total nitrogen absorbed (N efficiency relative to the number of grains) was lower with Pression. Other authors have also noted such a difference in N efficiency between varieties [25, 28]. We accounted for this in our analyses, correcting for the variety effect in our inter-year comparisons.

2.2. Analysis of yield and protein concentration variability

The components and variation factors analysed for yield and protein concentration in the grains (Prot) were [22, 41]: total absorbed N (TOT N – kg·ha^{-1}), weight per grain (W1G – mg), nitrogen harvest index (NHI = GRN/TOT N, where GRN = nitrogen in the grain); and nitrogen efficiency relative to the number of grains (EFF = NG/TOT N – grains·g^{-1}, where NG = number of grains·m^{-2}).

$$\text{Yield} = \text{NG} \times \text{W1G} = \text{EFF} \times \text{TOTN} \times \text{W1G} \qquad \text{(Eq. (1))}$$

$$\text{Prot} = 6.25 \times (\text{GRN} / \text{Yield})$$

$$\text{Prot} = 6.25 \times \text{NHI} \times \text{TOTN} \times (1 / \text{Yield})$$

$$\text{Prot} = 6.25 \times \text{NHI} \times (1/ \text{EFF}) \times (1 / \text{W1G}) \qquad \text{(Eq. (2))}.$$

Variations in W1G were analysed by comparison with a reference grain weight (max W1G) depending only on the number of grains·m^{-2} (NG). Taking all the data available from trials run in the region [32, 59] and our survey fields, combining the results with the varieties Volga and Pression, we determined the boundary curve according to the number of grains per m^2 (Fig. 1) [8, 33]:

Equation (3)

(1) if NG < 17 000 gr·m^{-2} max. W1G = 46 (mg)

(2) if 17 000 < NG < 26 000 gr·m^{-2} max. W1G = 66 – (1.2 NG/1000) (mg)

(3) if NG ≥ 26 000 gr·m^{-2} max. W1G = 91 × 10^4 (1/NG) (mg).

Up to 17 000 grains·m^{-2}, competition between grains is weak and W1G can reach its varietal potential of 46 mg. Above 26 000 grains·m^{-2}, maximum yield is considered to have been reached (9.1 tons of dry matter per hectare).

2.3. Measurements

The cropping practices used on the fields were decided by the farmers. They informed us of the dates, application rates and implements used during the crop season.

An area of 2000 to 3000 square meters was defined in a uniform part of the field. At each location, we randomly selected sites for 20 micro-plots 50 cm long by 2 rows wide, avoiding areas crossed by the fertiliser spreader. Ten of the micro-plots were harvested at the flowering stage (stamen dehiscence); once the roots had been removed, the aerial parts were dried for 48 hours at 85 °C and weighed. The ten other micro-plots were harvested at physiological maturity ("wax-ripe" stage), to measure yield and yield components. After threshing ear by ear, the grains from each micro-plot were counted, dried for 48 hours at 85 °C and weighed. A sample of 100 plants randomly selected in the areas around the micro-plots was used to estimate the harvest index, the N content of grains and straw, and the isotopic composition of the carbon in the straw. After separating roots, straw and ears and threshing the ears, all the aerial parts were dried at 85 °C for 48 hours and then weighed. The N content of the aerial parts at flowering, of straw and ears at harvest, and of the grains, was measured by the Kjeldahl method.

The isotopic composition of the sample carbon is the relative difference between the isotopic ratio of the sample ($R = {}^{13}C/{}^{12}C$) and that of an international benchmark (Pee Dee belemnite rostrum). Values were expressed as $\delta^{13}C = (R_{sample} - R_{standard})/R_{standard}$.

The value of the discrimination ($\Delta^{13}C$) was obtained from the isotope ratio of the sample ($\delta^{13}C$) and the carbon isotope composition of air:

$\Delta^{13}C$ (straw) = $\delta^{13}C$ (atmospheric CO_2) – $\delta^{13}C$ (straw)/ (1 + $\delta^{13}C$ (straw)).

From this isotopic discrimination one can evaluate the occurrence of variations in stomatal conductance when the carbon assimilates are allocated to the plant part on which the measurement is carried out. So, $\Delta^{13}C$ (straw) can help to

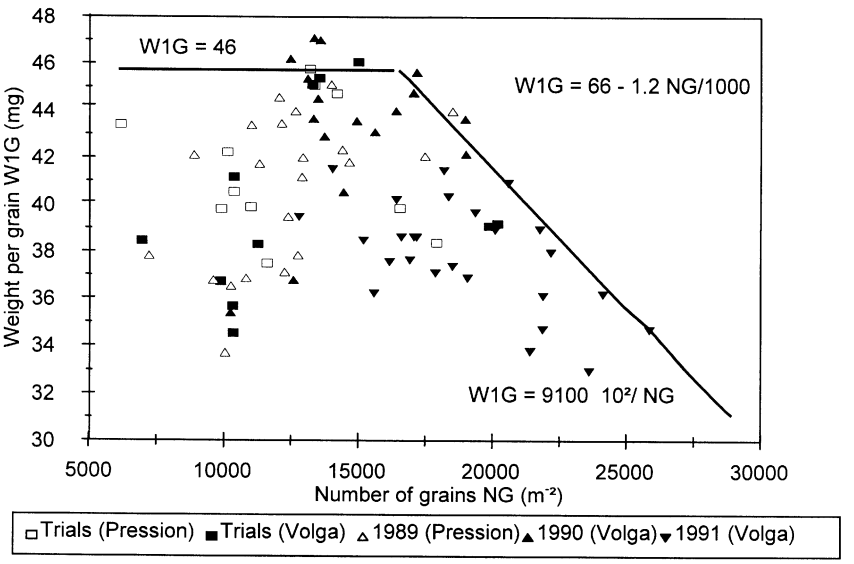

Figure 1. Boundary curve of the weight per grain (W1G) as a function of the number of grains (N1G) (Trials [32, 59] and network of farmers' field 1989-1990-1991).

identify the impact of temporary water shortage before anthesis (period of growth of the vegetative structure) [16, 21].

Any lodging and weed infestation were noted at flowering and at the end of grain filling. Weeds were recorded, noting species, and number of heads for monocots or percentage ground cover area for dicots. The scale of severity ranged from 0 to 4. Lodging was scored 0 to 9, with the percentage of the micro-plot affected (S) and the angle of lodging (angle between stems and ground, in degrees (a)): Lodging score = (90 – a) × S/1000.

Diseases of leaves and stems and root necrosis were measured 300 degree days after flowering. Diseases of the last two leaves were assessed by visual scoring of the percentage of leaf surface diseased. Stem diseases were assessed by the percentage of stems that were necrotic on at least 1/3 of their thickness. For root necrosis, we noted the percentage of stems with at least one necrotic root.

Physico-chemical analysis of the topsoil gave the texture (in five particle size grades), organic carbon (Anne method: oxidation in 8% $K_2Cr_2O_7$ with H_2SO_4 solution), total N (Kjeldahl method), pH (water), total $CaCO_3$, assimilable phosphorus (usually Dyer method: 2% citric acid extract, 10 mL per 1 g of fresh soil; Joret Hébert method for lime-rich soils: 1/5 M NH_4 oxalate extract, 25 mL per 1 g of fresh soil), and exchangeable magnesium and potassium. The quantity of mineral N in the soil (nitrate or ammonia N) was analysed in February once winter moisture had drained from the uppermost three horizons (0–30 cm, 30–60 cm, 60–90 cm), from an extraction with 1 M KCl on a mixture of four cores per horizon and per station.

For each field, a soil profile pit was dug, perpendicular to the direction of ploughing, 2.5 to 3 metres wide and 1.2 metres deep [23], near the zones where plants were sampled, to assess rooting quality and soil structure. The observation face was divided into 2 cm × 2 cm squares, and each square scored according to whether or not it contained roots [56]; the rooting depth taken to calculate the nitrogen and water balance sheets was the depth below which there was an average of less than 1 root per 20 cm on a horizontal line. Soil structure was observed using the method recommended by Manichon [23, 46], which is based on visually distinguishing soil masses in the topsoil, according to the way their structural elements are assembled and their internal porosity. The relative area occupied by each type of structural state on the observation face was noted; the proportions of the most unfavourable states, CΔ (massive structure, very few pores) and BΔ (clods some ten centimetres across with few pores, separated by cavities of about a centimetre) were, on the basis of Wibawa's results [59], used to analyse variations in nitrogen absorption.

Lastly, daily weather data were recorded at the stations of the French national weather network (Météo France), nearest each field: precipitation, minimum and maximum temperatures and evapotranspiration.

The amount of available nitrogen of each field was evaluated, summing mineral N measured at the end of winter (cumulated on the maximum rooting depth), net mineralisation estimated by the AZOBIL® software package [35] and N fertiliser. The maximum soil water store was calculated by knowing soil texture and maximum root depth. Changes in the soil water store over the course of the cropping cycle were estimated using a two-compartment model and a ten-day water balance sheet taking into account precipitation, potential evapotranspiration and the development stage of the crop [12].

2.4. Statistical treatments

The statistical treatments of the data were effected with the STATGRAPHICS® software package. The relationships between yield and grain protein concentration and their respective components, and the relationships between these

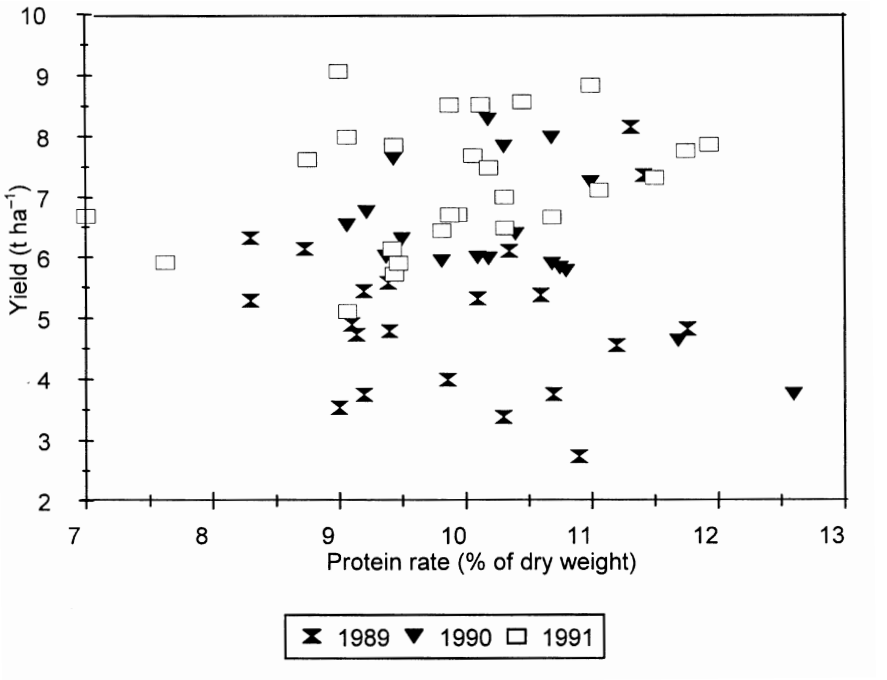

Figure 2. Grain yield and grain protein rate variability (network of farmers' fields 1989 to 1991).

components and environmental factors, were treated by simple and multiple linear regression when they were quantitative variables. When the explanatory variables were qualitative, we carried out analyses of variance.

3. RESULTS

3.1. Yield and grain protein concentration

The fields chosen covered a wide range of yield and grain protein concentration combinations (Fig. 2). Over the three years and the 65 fields of our experiments, yield varied by 300% (between 2.74 and 9.08 t·ha^{-1} of dry matter) while protein concentration varied between 7 and 12.6% of the grain dry matter. The coefficients of variation for yield decreased from 1989 (mean: 5.05 t·ha^{-1}; coefficient of variation: C.V. = 26%), to 1990 (mean: 6.38 t·ha^{-1}; coefficient of variation: C.V. = 18%) and to 1991 (mean: 7.23 t·ha^{-1}; coefficient of variation: C.V. = 14%), while those for protein concentrations remained fairly stable (C.V. < 10% for grain protein concentration means of 9.9% (1989); 10.3% (1990); 9.9% (1991)).

3.2. Growth conditions

From year to year, the experiments offered a wide range of crop growth conditions (Figs. 3 and 4).

In 1989, the winter was mild and the spring very warm and wet. Sowing began in February, was interrupted by rain in late February and early March, and began again after March 10th (Fig. 4.a). The late-sown fields flowered later and their water reserves were lower at flowering (Fig. 4.b).

In 1990, the winter was mild and wet. In the spring, rainfall was slight and irregular. Sowing dates were clustered in late February and early March. According to the water balance sheet, most of the fields had less than 40% of their initial water stores at flowering (Fig. 4.b).

In 1991, the winter was dry and cold. In the spring, rain was regular. Sowing dates were close and rather late, but weather conditions at the stem elongation stage and flowering reduced the risk of moisture deficit. Nearly 80% of the fields still had over 40% of their initial water store at flowering (Fig. 4.b).

3.3. Three-stage analysis

The analysis of the effects of environment and crop management on the components of yield and protein concentration was conducted in three stages [6, 18, 40]:

(a) identifying the yield and quality components that best explained variations in output;

(b) identifying the environmental conditions and factors that acted on these components;

(c) specifying the characteristics of the cropping system, soil and climate that helped to create favourable or unfavourable environmental conditions.

3.3.1. Relationship between yield, protein concentration and their components

Table III shows the main correlations between the final variables and their components for the three years of our experiments. There was little correlation between grain protein and yield. In all three years, absorbed nitrogen

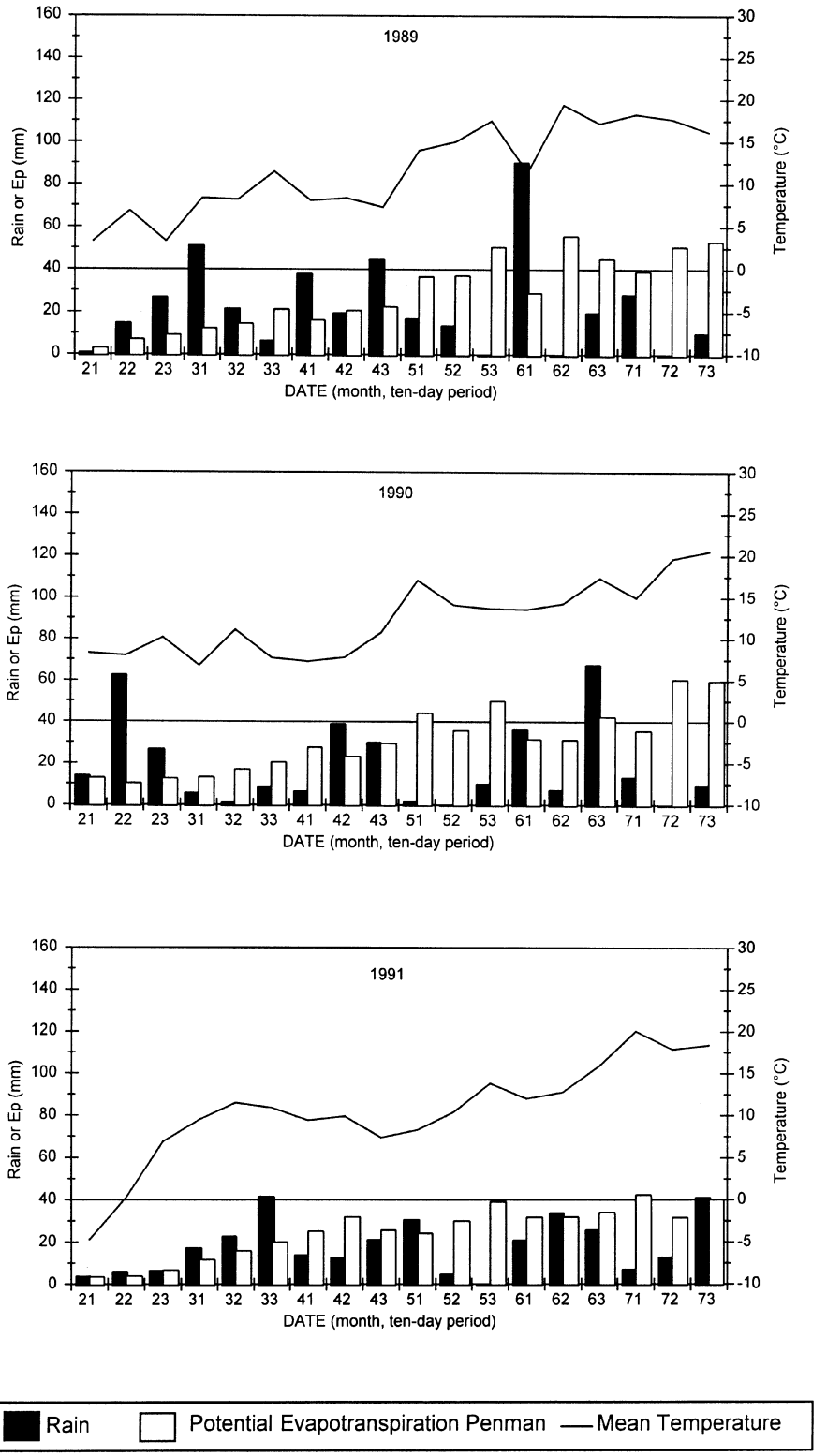

Figure 3. Climatic data for ten-day periods in the meteorological station of Trumilly (Picardie).

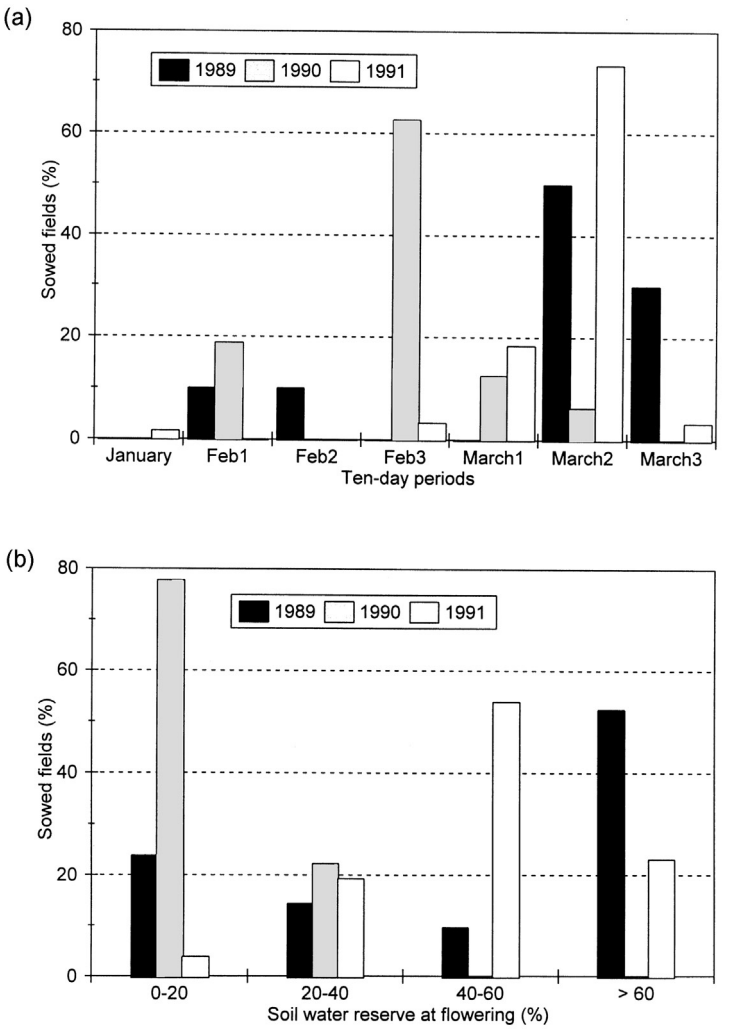

Figure 4. (a) Date of sowing (network of farmers' field – 1989 to 1991); (b) level of soil water reserves at flowering according to the water balance sheet (farmers field network – 1989 to 1991).

(TOT N) was most closely correlated with yield, and the efficiency of absorbed nitrogen relative to the grain number (EFF) most closely correlated with grain protein. NHI varied little (C.V. = 5% in all three years) and this variable shows little correlation with either yield or grain protein concentration. Linear models, explaining at least 80% of the yield and grain protein variance, are given in Table IV: yield is primarily explained by absorbed nitrogen and, to a lesser extent, by nitrogen efficiency relative to the number of grains. Grain protein is primarily explained by nitrogen efficiency relative to the number of grains and, to a lesser extent, by mean grain weight.

3.3.2. Analysis of variations in yield and grain protein components. Environmental effects

Nitrogen efficiency relative to the number of grains (EFF) varied widely from year to year and field to field (Tab. V). We tested five factors in a forward stepwise regression: the total nitrogen absorbed (TOT N); the proportion of nitrogen absorbed before flowering; the $\Delta^{13}C$ of the straw; the % CΔ and % BΔ in the soil profile. These factors did not carry the same weight each year in the final statistical model. In 1989, the total nitrogen absorbed and the $\Delta^{13}C$ of the straw at harvest explained 60% of the variance. The soil structure had an effect on efficiency in 1990, but not in 1989 and 1991. In 1991, the total nitrogen absorbed and the percentage of nitrogen absorbed before explained 56% of the variance of the N efficiency (Tab. V).

The total amount of nitrogen absorbed (TOT N) depended on the amount of nitrogen available in the environment and the nitrogen absorption conditions. The year effect on this variable was significant (Tab. V). Four fields with particular limiting factors were excluded from the analysis: two were very deficient in Mg (1 in 1989, 1 in 1990) and in 1989 two had a weed score of over 3 at harvest. To explain the amounts of nitrogen absorbed in the other fields, a multiple stepwise regression was carried out with three

Table III. Determination coefficient for simple linear regressions between yield and grain protein concentration components (network of farmers' field 1989 to 1991).

1989 21 fields	R^2 (%)	Yield	Protein concentration PROT	N absorbed N TOT	N Efficiency for grain number EFF	Grain weight P1G
	Protein concentration	< 10				
	N absorbed	78 (+)	27 (+)			
	N Efficiency for grain number	< 10	80 (–)	48 (–)		
	Grain weight	49 (+)	11 (–)	16(+)	< 10	
	N Harvest Index	46 (+)	< 10	15 (+)	< 10	67 (+)
1990 18 fields	R^2 (%)	Yield	Protein concentration PROT	N absorbed N TOT	N Efficiency for grain number EFF	Grain weight P1G
	Protein concentration	27(–)				
	N absorbed	67 (+)	< 10			
	N Efficiency for grain number	< 10	68 (–)	< 10		
	Grain weight	31 (+)	40 (–)	< 10	< 10	
	N Harvest Index	23 (+)	33 (–)	< 10	20 (+)	64 (+)
1991 26 fields	R^2 (%)	Yield	Protein concentration PROT	N absorbed N TOT	N Efficiency for grain number EFF	Grain weight P1G
	Protein concentration	< 10				
	N absorbed	61(+)	62 (+)			
	N Efficiency for grain number	< 10	81 (–)	48 (–)		
	Grain weight	< 10	14 (–)	21 (+)	< 10	
	N Harvest Index	< 10	< 10	17 (–)	12 (+)	19 (+)

The sign (+) or (–) mean respectively positive or negative relation.

Table IV. Forward stepwise regression for yield and grain protein concentration (network of farmers' fields 1989 to 1991).

	Yield ($t \cdot ha^{-1}$)				Grain protein concentration (%)			
	Constant	Coefficient 1st variable TOT N	Coefficient 2nd variable EFF	R^2: Multiple determination coefficient	Constant	Coefficient 1st variable EFF	Coefficient 2nd variable W1G	R^2: Multiple determination coefficient
1989	– 6.65	4.2×10^{-2}	6.5×10^{-3}	91%	23.5	-9.6×10^{-3}	– 0.11	90%
1990	– 7.11	3.7×10^{-2}	8.3×10^{-3}	88%	25	-9.9×10^{-3}	– 0.15	91%
1991	– 3.83	3.1×10^{-2}	5.1×10^{-3}	81%	23.8	-7.8×10^{-3}	– 0.16	90%
1989-91	**–3.47**	$\mathbf{3.4 \times 10^{-2}}$	$\mathbf{4.4 \times 10^{-3}}$	**89%**	**24**	$\mathbf{-7.7 \times 10^{-3}}$	**–0.16**	**87%**

factors: available nitrogen, % CΔ and % BΔ in the soil profile. Table V shows that knowing the available nitrogen and % CΔ, one can explain roughly 80% of the variability in the total nitrogen absorbed in 1989 and 1991. For 1990, the nitrogen available in the soil was significant, but explained only 30% of the variability in absorbed nitrogen. Introducing the soil structure did not improve the explanatory performance of the statistical analysis.

Analysis of variance of the year effect on the ratio of **mean grain weight (W1G)** to the maximum W1G from the boundary curve (see Eq. (3) and Fig. 1) showed significant differences (1990 is higher than the other years; see Tab. V

Table V. Forward stepwise regression between the three key-components of yield and grain protein concentration and environmental conditions.

Environmental conditions tested	Year effect (1)	Mean ± confidence interval	R^2	Coefficients for each variable	Constant	*P*–value (%) (2)
EFF						
1989 (21 fields)	b	942.1 ± 44.3	60		–680	3×10^{-4}
NTOT ($kg \cdot ha^{-1}$)				–2.6**		
ΔC^{13} (‰)				98.6**		
1990 (18 fields)	a	842.3 ± 35.2	30		920	5×10^{-2}
% CΔ soil structure				–1.4**		
% BΔ soil structure				– 0.9*		
1991 (26 fields)	c	1039.4 ± 54.1	56		1230	3×10^{-4}
NTOT ($kg \cdot ha^{-1}$)				–2.1**		
% N after flowering				2.5**		
1989-1990-1991 (65 parcelles)		1005.1 ± 37.1	44		–356	$< 10^{-4}$
NTOT ($kg \cdot ha^{-1}$)				–2.1**		
ΔC^{13} (‰)				77.6**		
% N after flowering				1.5**		
N TOT						
1989 (18 fields)	a	138.6 ± 18.5	76		66.4	$< 10^{-4}$
N available ($kg \cdot ha^{-1}$)				0.54**		
% CΔ soil structure				–0.71*		
1990 (17 fields)	b	175.2 ± 14.5	30			$< 10^{-4}$
N available ($kg \cdot ha^{-1}$)				0.85**		
1991 (25 fields)	b	186.6 ± 16.7	83			$< 10^{-4}$
N available ($kg \cdot ha^{-1}$)				0.90**		
% CΔ soil structure				–0.65**		
1989-1990-1991 (60 fields)		169.5 ± 11	74			$< 10^{-4}$
N available ($kg \cdot ha^{-1}$)				0.87**		
% CΔ soil structure				–0.34*		
WIG / max WIG						
1989 (21 fields)	a	88.7 ± 3.4	61		112	2×10^{-4}
flowering temperature (°C)				–0.87**		
roots necrosis rate (%)				–0.12*		
1990 (18 fields) (3)	b	95.2 ± 3.5				
1991 (26 fields)	a	89.7 ± 2.4	62		111	10^{-4}
thickness plough pan (cm)				–1**		
% CΔ soil structure				–0.16**		
roots necrosis rate (%)				–0.10**		
% flowering water balance				–0.19**		
1989-1990-1991 (65 fields)		91 ± 7.2	33			$< 10^{-4}$
roots necrosis rate (%)				–0.12*		
flowering temperature (°C)				–0.6**		

(1) In the "year effect" column two different letters indicate that annual means are significatively different (for a 95% confidence level (Newman-Keuls)).
(2) *P* value (for a 95% confidence level) * < 5%, ** < 1%.
(3) For 16 fields the W1G/maxW1G ratio is more than 90% and the two 80% fields are marked by very high temperature during flowering.

Table VI. Mean and variation for N application rates by farmers and N supply in the soil evaluated by AZOBIL®.

	1989	1990	1991	TOTAL
Number of fields	21	18	26	65
Mean N application rates ($kg \cdot ha^{-1}$)	110.7	107.8	111.9	110.4
Standard deviation	12.2	20.8	14.9	16.3
Mean N supply evaluated ($kg \cdot ha^{-1}$)	81.6	101.4	89.7	90.4
Standard deviation	43.3	34.7	25.7	35.5
Mean total N available ($kg \cdot ha^{-1}$)	192.3	209.2	201.6	200.7
Standard deviation	46.5	40.0	21.8	37.1

Table VII. Part of compacted soil profile (% CΔ) in relation to the rain during the ten-day period before sowing and implement.

	1989			1990			1991		
	SW	CW	Test*	SW	CW	Test	SW	CW	Test
Rain ten days before sowing < 30 mm	28.5 (11)	39 (1)	ns	19 (7)	26 (2)	ns	27 (14)	28 (10)	ns
Rain ten days before sowing > 30 mm	15 (2)	50.4 (7)	s	36 (8)	67 (1)	s	20 (1)	48 (1)	
Test	ns	s		ns	s		ns	ns	

( ) number of fields; SW: simple wheels; CW: combine wheels.

* T-test (for a 95% confidence level).

year effect column). To explain, each year, the variability of the ratio "W1G/maximum W1G", we tested nine factors in a forward stepwise regression (Tab. V):

- for each of the three ten-day periods after flowering, the mean of maximum temperatures and the plant-available soil water store (as a % of the maximum);
- the rate of root necrosis;
- the thickness of the plough pan;
- the compacted percentage of the topsoil (% CΔ).

For 1989, the maximum temperature between anthesis and maturity and the rate of root necrosis explained over 60% of the [W1G/Reference weight] ratio's variability. For 1990, maximum temperatures explained the smallness of the [W1G/Reference weight] ratio for the only two fields where this ratio was below 90%. For 1991, conditions for root absorption (soil structure, soil moisture and necrosis) explained 60% of the variability of [W1G/Reference weight].

3.3.3. Effects of cropping system on environmental conditions

The variations in the **available nitrogen amount** between different fields in the network were linked to the fact that farmers did not fully adapt their fertiliser inputs to the estimated level of soil N supply, especially in 1989 and 1990. For both these years, the variation coefficients of nitrogen application rates were only half as much as the variation coefficients of the soil N supply calculated by the AZOBIL® software package [35] (Tab. VI). In 1991, on the other hand, a little less was applied on fields with a good soil N supply, reducing the variability of total available N compared to the other years (Tab. VI).

As regards **soil structure** (Tab. VII), soils were most compacted (measured as % CΔ) in fields where the crop was sown in wet conditions (more than 30 mm of rainfall in the 10 days before sowing) with a combine-wheel tractor (wheel width 60 to 100 cm). These adverse conditions particularly affected sowings carried out between 11 and 14 March in 1989, sowings in the last ten days of March in 1990, and in 1991 only the last two fields sown.

Water supply before flowering was assessed by isotopic discrimination of the straw carbon, for which the mean values were significantly lower in 1989 (20.15 $\sigma = 0.56$) and 1990 (19.96 $\sigma = 0.49$) than in 1991 (21.02 $\sigma = 0.39$). There was a correlation ($R^2 = 43\%$) between this indicator and the minimum available soil water during the six weeks before flowering, expressed as a percentage of the full plant-available soil water store (estimated by the water balance sheet). The situations of most severe deficit were characterised in 1989 by a combination of late flowering (after 10 June) and an available soil water store of less than 130 mm. The very severe deficits of 1990 were mainly linked to small available soil water stores, and in one case a late sowing date. Small available soil water stores were also an unfavourable factor in 1991, but to a lesser extent since the weather that year was cooler and wetter.

The most obvious **crop health** problem in our experiments was root necrosis attributed to take-all (*Gaeumannomyces graminis* (Sacc) v. Arx G. Olivier). In principle, take-all develops more easily in sandy soils [34]; we therefore excluded some sandy fields from the analysis of the cropping system

Table VIII. Analyses of variance for cropping systems effect on root necrotic rate due to take-all.

Chronology: preceding crop – previous preceding crop							
	host-host or host-amplifier		host-non host		non host-non host		All cropping succession
	number of fields	necrotic rate	number of fields	necrotic rate	number of fields	necrotic rate	necrotic rate
1989	12	57[a]	6	27[b]	2	15[b]	44
1990	8	18[a]	5	7[b]	2	5[b]	13
1991	6	50[a]	8	19[b]	7	16[b]	27

Two different letters indicate that means are significatively different (95% confidence level (Newman-Keuls)).

effect shown in Table VIII. Following Colbach et al. [13], we classified cropping systems according to the nature of the previous two crops: "host" crops (wheat, winter barley, spring barley) or "amplifier" crops (maize). The rate of root necrosis was systematically higher where the preceding crop was a "host" crop and the one before that either a "host" crop or an "amplifier" crop, than where the preceding crop was a "host" crop and the one before that a "non-host" crop (such as peas or beet), or where neither of the previous two crops was a "host" crop. This effect is systematic regardless of the year, although the overall intensity of the problem varied, 1989 and 1991 having the highest rates of necrosis.

4. DISCUSSION

Our goals were to characterise and explain the variability for grain yield and grain protein concentration in spring barley on the scale of a production region, and rank the cropping system and environmental factors.

4.1. Variation in yield and grain protein

A first result is that, on the scale of a farming region 70 km by 40 km, yield and grain protein vary considerably owing to interactions between farming methods, soils and weather. For the 65 fields in the three-year farmer network, the coefficient of variation for yield was 25% and the coefficient of variation for grain protein was 11%; this order of magnitude is comparable to or greater than the inter-genotype variations reported in the literature [5, 19, 29, 50]. Also, once the cultivar was fixed, the yield and quality of spring malting barley were not linked: for a high yield of over 6 $t \cdot ha^{-1}$ of dry matter (i.e. 7 $t \cdot ha^{-1}$ at 14.5% humidity), grain protein might be high or low.

4.2. Four environmental characteristics explained poor performance

A second result concerns the interactions between cropping methods and environment that cause poor performance in terms of yield, grain protein and grain size. Besides the already-known effects of nitrogen on yield and grain protein, we demonstrated that three other elements in the cropping system, in combination with environmental factors rarely mentioned in the literature, also had marked effects. These were topsoil structure, crop water supply and take-all.

4.2.1. Nitrogen

Yield was affected if too little nitrogen was absorbed, and this was the main limiting factor in the three years studied (and matches the observations of Lauer and Partridge [31] and Varvel and Stevenson [58]). But if too much nitrogen was available and was absorbed, this did not further increase yield but did increase grain protein [19, 58], especially if, by generating strong growth in the vegetative structures, it exacerbated water stress at the end of the growing cycle [9]. These effects were not very noticeable in 1990, when the quantities of nitrogen absorbed were less variable; they were much more so in the other two years. In 1989 and 1991, five fields had more than 250 kg of nitrogen with no obstacle to absorption, and grain protein in those fields was over 11% compared to an average of 9.9% for the entire set of fields for both years. The effect on grain protein of post-flowering absorption was observed two years out of four by Bulman and Smith [10]. Uncommon in our experiments, since N fertilisation was generally applied once only and at sowing, this effect of post-flowering absorption was only observed in 1991, where the low water deficit favoured late nitrogen absorption.

The variability in available N was linked to farmers' fertiliser application practices in interaction with environmental conditions left by the preceding crops. In 1989 and 1990, the N rates farmers applied took little account of the soil supply, which in fact varied widely depending on residue at the end of winter, the nature of the crop rotation and the management of the residues (40 to 230 $kg \cdot ha^{-1}$ estimated by AZOBIL$^{(r)}$ for 1989 and 1990). Some preceding crops that can mineralise with a high degree or unpredictably (e.g. pasture and peas), or recent input of organic matter, may entail a risk of increasing N supply to an extent that is hard to predict [17, 57]. In 1991, when farmers were informed of the results from the first two years and given a method for calculating N application rates, they took better account of the variability of soil supply in deciding their fertiliser application rates.

4.2.2. Soil structure

In 1989 and 1991, for a given amount of available N, a compacted soil profile led to a drop in yield, mainly due to fewer grains per square meter. In these two years, between

situations where less than 40% of topsoil volume was of very low porosity (state CΔ in Coulomb et al. [15]) and situations with more than 40% CΔ, there was a mean loss of 20% in the number of grains per square meter and a yield loss of 15%. According to the literature, plants also respond to a continuous, compact soil structure with reduced growth of aerial plant parts, which is attributed either to reduced water availability affecting stomatal conductance and dry matter production [38, 43, 55] or reduced N absorption [2, 59].

For these two years, the reduction in absorbed N due to compaction was 10% for every 15% increase in the compacted volume (CΔ) (between 30 and 70%). With winter wheat, Meynard and Aubry [39] note reductions of 25% of absorbed N if over 40% of the soil profile is compacted. In 1990, on the other hand, when the weather before flowering was dry, compacted soils did not reduce N absorption but N efficiency. Consequently, that year, fields with compacted soils yielded higher grain protein (10.1% σ = 0.7 on uncompacted soils, 11% σ = 0.8 on compacted soils), whereas soil structure had little effect on grain protein in the other two years (1989, uncompacted: 10.1% σ = 1.1, compacted: 9.7% σ = 0.9; 1991, uncompacted: 10% σ = 1.0, compacted: 9.6% σ = 1.2). Wibawa [59], on trials combining different levels of N fertilisation and various soil structures, observed that, when the spring was wet, N absorption by barley was particularly reduced by compacted soils (i.e. where state CΔ predominated). When the spring season was dry, soil structure had less effect on N absorption than on the efficiency of absorbed N relative to grain number, soil structure combining blocks and cavities (state BΔ predominant) being the most unfavourable. This reduction in N efficiency, correlated in Wibawa's experiments [59] with a drop in $\delta^{13}C$ in the straw, could be due to increased water stress in the crop. This hypothesis is consistent with the work of Tardieu [55] and Masle and Farquhar [37].

The main cause we identified for compacted soil profiles (over 40% of CΔ in the profile volume) was adverse sowing conditions in spring. Slow-draining fields where farmers worked in over-wet conditions using combine-wheel tractors and making several tillage passes after ploughing, which was a typical situation in 1989, had large compacted masses in the profile. Soane et al. [52] have also noted (in Scotland) that farmers make a number of passes to prepare the seedbed for spring barley. We made no precise measurement of soil moisture but the literature shows that differences in soil moisture of a few percent can make a significant difference to the severity of soil compaction. Blackwell, cited by Soane et al. [51], shows that an increase of 5% soil moisture, from 14 to 19%, causes differences in bulk densities of 10 %. Papy [44] notes that the percentage of type CΔ massive structures is 2.5 times greater where mean soil water is 26% than where it is 23%. For fields where a preceding crop (especially beet or maize) was harvested in wet conditions, ploughing and shallow tillage in dry conditions in spring, as in 1990, generate a type B soil structure with compact blocks separated by cavities [15, 36].

4.2.3. Crop water supply

The third factor in reduced yields or excess grain protein was crop water supply both before and after flowering.

The water deficit before flowering was estimated by the carbon isotope discrimination of straw ($\Delta^{13}C$). This indicator, correlated with the water balance, explained well the N efficiency relative to the number of grains for a given quantity of N absorbed, in 1989 and for the three years grouped together. The $\Delta^{13}C$, as an indicator of water stress, has already been used to compare the water-use efficiency of various genotypes [21], but it is, to our knowledge, the first time that it has been used to compare environmental conditions of fields in an on-farm network. Several authors also note a negative correlation between protein concentration and water balance or the amount of soil water (on wheat [1]; on barley [19]; on wheat and rye [22]). Fowler et al. [22] specify that measurements of root zone water during stem elongation and pan evaporation (2 weeks prior to maturity) explained 73% of the variability observed in grain protein concentration. After flowering, a water deficit combined with high temperatures results in early ripening that affects grain weight, so reducing yield and concentrating protein in the grains [20, 49, 53, 54]. These effects were particularly marked in late-sown fields in 1989 and 1990. In 1991, however, although there was no water deficit, some soil profiles showed discontinuities between the topsoil and deeper horizons (plough pan) and/or compaction in the plough layer, which might explain certain deficits in mean grain weight due to poor water absorption conditions. With maize, Tardieu and Manichon [56] note that compacted areas in the plough layer are not colonised by roots and that in the underlying horizons root distribution is disturbed directly underneath compacted areas. Wibawa [59] observed a similar phenomenon, though less marked, with spring barley. This irregular distribution leads to water stress even when most of the root zone is still moist [55].

The water deficit depends on a combination of the year's weather conditions, the soil's potential water store, and sowing date. In 1989, when the plant-available soil water store was below 100 mm, and in 1990 when it was below 130 mm, late sowing (March) resulted in higher grain protein concentration and lower grain weight, as has also been observed by Leterme et al. [33] and Zubrisky et al. [60]. On the other hand, in a year without water stress, like 1991, postponing the sowing date had no effect on grain protein, as Lauer and Partridge pointed out [31]. A frequency study of the weather between 1975 and 1994 in the region [32] shows that in five years out of ten, the water deficit is equal to or greater than 70 mm in the third ten-day period of May (spike emergence in spring-sown barley), and equal to or greater than 100 mm in the second ten-day period of June (flowering of March-sown barley); this makes water stress during stem elongation or ripening a significant risk for late-sown fields, especially on soils with small water stores.

4.2.4. Take-all

Root necrosis at a rate of over 30% due to *Gaeumannomyces graminis* had a negative impact on grain weight; this effect was previously recorded mainly with winter wheat [26, 45]. By reducing the roots' capacity to absorb water and nitrogen, take-all reduces the photosynthetic capacity of the leaves too early and so slows down grain filling [24, 47]. Table VIII shows that the two preceding crop species affected the rate of

Table IX. Criteria for field choice.

Soil to avoid (ranked)	Reasons	Worse conditions
Soil Water reserve < 100 mm	1 year out of 2, water stress before 20 may, affecting N efficiency	Late sowing
Hydromorphic soil	Slow-draining, risk of soil compaction at sowing	Too early sowing with combine wheels

Crop chronology to avoid (ranked)	Reasons	Worse conditions
Preceding crops (peas and pasture), recent livestock manure	Soil N supply hard to predict	No residual N at the end of winter measure
Two preceding crops: cereals or corn/cereals	Risk of take-all affecting grain weight	Too early sowing and sandy soils

necrosis; this is consistent with the results of Colbach et al. on wheat [14]. Year-to-year differences (1990 was much less heavily infested than 1989 or 1991) can doubtless be explained by the amount of precipitation in winter and spring. Dry conditions inhibit the spread of take-all [42].

4.3. Conditions for obtaining high yield combined with low grain protein

Thus low grain protein went hand in hand with high yield where there were (i) a well-adjusted quantity of available nitrogen (180 to 250 $kg \cdot ha^{-1}$ for the region under consideration), (ii) favourable absorption conditions and (iii) the right amount of water available during stem elongation. The 17 fields in our study that had these characteristics (all three years together) gave a mean yield of 7.22 $t \cdot ha^{-1}$ ($\sigma = 0.8$) and a mean grain protein concentration of 9.7% ($\sigma = 0.5$). By contrast, high grain protein and high yields went together when fields had both large amounts of available N (over 250 $kg \cdot ha^{-1}$) and favourable absorption conditions (CΔ percentage below 40%, no plough pan). The ten fields that displayed these characteristics gave a mean yield of 7.19 $t \cdot ha^{-1}$ ($\sigma = 0.6$) and grain protein concentration of 10.7% ($\sigma = 0.7$). But poor N absorption conditions combined with water stress during stem elongation and ripening led to low yield and fairly high grain protein levels. The nine fields with these characteristics yielded 4.15 $t \cdot ha^{-1}$ ($\sigma = 0.6$) at a grain protein concentration of 10.6% ($\sigma = 0.6$).

4.4. Technical recommendations

From the above results it emerges that the main technical choices for achieving yield and protein concentration targets simultaneously concern three interconnected levels of decision: the choice of fields to be sown with spring barley, choice of tillage methods and sowing date, and choice of fertiliser application rate. It is mainly this latter factor that is dealt with in the agricultural extension literature [7]. The farmers in our experiment applied similar programmes for growth regulator, herbicide, fungicide and insecticide. Except for two fields in 1989, in which very heavy weed infestation probably reduced the NG (the mean NG for these two fields was 9800 grains$\cdot m^{-2}$, as opposed to an overall average of 12600 grains$\cdot m^{-2}$ that year), weeds, lodging and foliar diseases were kept well under control by up-to-date methods.

For choice of field, Table IX summarises the field characteristics to be avoided in view of the risks they represent for yield and grain protein. From the study it emerges that to reconcile high yield with low protein concentration, spring barley should not be grown in fields with small water stores (RU < 100 mm), or on slow-draining fields, where there is a high probability of compaction at sowing. Some crop chronologies are unfavourable to malting barley: previous crops that leave high levels of N that are hard to predict, even with the predictive balance sheet method, are also best avoided. Fields where both the preceding two crops were favourable to the development of take-all are not recommended, but have less impact on protein concentration than fields with excess nitrogen.

The earliest possible sowing date is determined by the risk of frost on seedlings. In practice, farmers in this region do not start sowing before 10 February, so saving their crop from having to survive the coldest weeks of the year. The last date for sowing is worked out according to risks of water stress and of high temperatures at the end of stem elongation and during ripening. In the twenty years 1975-1994, the available water store emptied in the last ten days of June nine years out of ten where its maximum capacity was 100 mm, five years out of ten where its maximum capacity was 130 mm; and three years out of ten where its maximum capacity was 150 mm. With the varieties we studied, to ensure flowering before 5 June and so limit the risk of water deficit during grain filling, fields must be sown before 1 March. However, while rather late sowing entails a risk of higher grain protein and lower yield, on soils with a good water store these risks are low compared to those of compaction due to sowing before the field has fully drained.

Full control of nitrogen nutrition will affect the overall amount of N available and its absorption. We estimate nitrogen requirements at 210 $kg \cdot ha^{-1}$ for a potential of 17000 grains$\cdot m^{-2}$, assuming a mineral nitrogen residue of 30 $kg \cdot ha^{-1}$ and an average nitrogen efficiency relative to the mean number of grains (950 $gr \cdot g^{-1}$). In some fields of lower potential (rendzinas, cambisols or sandy sediments), the target number of grains can be reduced to 15 000 and N requirements to 190 $kg \cdot ha^{-1}$. The quantities to apply can be calculated by estimating the nitrogen balance with the AZOBIL$^{(r)}$ software

package [35]. For example, where mineral residual N in the soil at the end of winter is 45 $kg \cdot ha^{-1}$, the recommended fertiliser application rates vary, for a luvisol on loess deposits (high yield potential), between 105 $kg \cdot ha^{-1}$ (following a beet crop) to 150 $kg \cdot ha^{-1}$ (following a cereal crop with stubble ploughed in, or grain maize).

5. CONCLUSIONS

In an intensive farming region, with technically competent farmers who regularly achieve very good economic results with winter wheat or sugar beet, we found that there are still many problems in achieving combined control of yield and protein concentration in spring barley. Factors identified from an agronomic analysis were the place of barley in the rotation and the choice of the type of soil, the rules for working out N fertiliser application rates, and the choice of the sowing date (not too early, to avoid compaction; not too late, to avoid water deficit).

The regional agronomic diagnosis methodology, already tried and tested on several problems concerning analysis of yield variations (see the summary by Doré et al. [18]), was here adapted to a study of variations in the quality of an agricultural product. As the nature of limiting factors identified here for grain yield and protein concentration is probably not very different from one region to another, their hierarchy can be modified in other zones of production of spring barley with different soil characteristics, climate and cropping systems. The relationships established between the yield and proteins concentration components (nitrogen efficiency relative to number of grains, nitrogen absorbed, grain weight) and environmental characteristics might allow identification of those mechanisms in other regions. In particular, the study highlights the importance, in field conditions, of limiting factors for growth, yield and protein concentration such as a compacted topsoil and root disease, whose consequences crop physiologists are not yet very familiar with [30].

Lastly, this study covered the supply catchment area of a grain collecting firm. It enabled us not only to advise the farmers on improvements to farm practices, but also to design a new supply management strategy for the grain collecting firm: choosing fields, soil type and preceding crop to give a higher probability of satisfactory grain quality; and drawing up contracts requiring farmers to adopt particular practices identified as likely to achieve combined high yield and satisfactory grain protein levels.

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