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Muriel Valantin-Morison, J.M. Meynard. Diagnosis of limiting factors of organic oilseed rape yield. A survey of farmers' fields. *Agronomy for Sustainable Development*, 2008, 28 (4), pp.527-539. hal-00886399

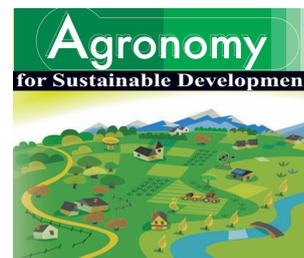
**HAL Id: hal-00886399**

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Submitted on 11 May 2020

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## Research article

# Diagnosis of limiting factors of organic oilseed rape yield. A survey of farmers' fields

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(Accepted 7 May 2008)

**Abstract** – The yield of organic winter oilseed rape (WOSR) crop is low and variable in organic farming, but the reasons responsible for this problem are not clear. Aiming to identify the factors affecting organic oilseed rape yields, we carried out a diagnostic study on a network of 19 farmers' fields in four contrasting regions of France over a two-year period. Weed density and biomass, nitrogen absorption by the crop and by weeds, and nutrient availability in the soil, as well as the occurrence of pests and diseases, were assessed at four developmental stages. A range of possible limiting factors throughout the crop cycle led us to use a regression procedure for different periods, using the yield components during spring and biomass during autumn as dependent variables. We identified factors limiting yield and the critical time points at which they acted, which has never been done. Yield variation was strongly correlated with number of grains.m<sup>-2</sup>. Dry biomass of weeds, nitrogen uptake by weeds and density of weeds appeared to explain 39% of variation in crop biomass in early winter, while pollen beetle and rape stem weevil damage explained 4.5% and 12% of variation in the number of flowers.m<sup>-2</sup> and the number of branches.m<sup>-2</sup>, respectively. Crop nitrogen deficiencies occurring before branching were strongly correlated with weed biomass in flowering. Analysis of covariance showed that sowing date, soil management and the quantity of organic manure application may have significantly affected the nitrogen nutrition index, nitrogen uptake by plants and ratio of weed biomass: a late sowing date and shallow soil tillage were related to a low crop nitrogen nutrition index and high ratio of weed biomass. From a practical point of view, this study demonstrated that it should be possible to reduce weed competition by ensuring that the amount of nitrogen in soil before sowing is around 100 kg/ha.

**winter oilseed rape / organic farming / yield variability / yield components / diagnosis / farmers' fields / nitrogen deficiencies / weed competition**

## 1. INTRODUCTION

Winter oilseed rape (WOSR) is not widely used in French organic farming as its yield is low and unpredictable. However, this crop is of potential value in terms of market requirements and agronomic potential. Its oil is particularly beneficial for human health as it contains omega 3 fatty acids (Renaud, 1996; Bourre, 1996). Moreover, oilseed rape cake is a source of low-cost proteins that could be used as a supplement to correct the protein deficiencies of cereals for animal feeding in organic farming. Besides, oilseed rape is of agronomic value for several reasons, some of which are particularly relevant in organic farming. First, the inclusion of oilseed rape in a crop rotation is known to be of benefit for the following wheat crop. Kirkegaard and Sarwar (1998), and Smith and

Kirkegaard (2002) demonstrated that, as for other brassicas, the glucosinolates present in crop residues have biofumigation potential, which may be effective against take-all (*Gaeumannomyces graminis*). Second, oilseed rape traps nitrate efficiently in autumn (Vos and Van der Putten, 1997; Dejoux et al., 2003), reducing the risk of nitrate leaching during winter. Moreover, oilseed rape residues also return large amounts of nitrogen to the soil after harvest (Trinsoutrot et al., 2000; Dorsainvil, 2002), which is interesting in low-input systems.

The major factors limiting oilseed rape yields in conventional farming are well documented (Merrien and Pouzet, 1988; Williams et al., 1991; Dejoux et al., 2003). Most of these studies have stressed the importance of abiotic factors such as nitrogen and water. They have identified the yield components affected by these limiting factors and the times at which these factors act. Indeed, spring deficiencies have a much greater effect on yield than autumn deficiencies because of their effects on the number of flowers and seed abortion (Colnenne et al.,

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2002). Biotic factors often affect the yield of organic crops (David et al., 2005). Weeds are generally thought to present the most serious threat to organic oilseed rape production (Penfold et al., 1995; Clark et al., 1999). Moreover, oilseed rape is known to be attacked by numerous insects, especially *coleoptera*, which are difficult to control without chemical treatments. Many studies concern the biology of *Delia* spp. (Doddall et al., 1996, 1998) and *Meligethes aeneus* (Nilsson, 1994; Ekbom and Ferdinand, 2003; Cook et al., 2004) but few studies have dealt with the application of such research to integrated pest management, except Cook et al. (2002).

Previous studies have investigated the factors affecting oilseed rape yield in conventional agriculture, but no such research has been carried out on organic oilseed rape. In this study, we aimed to identify the major factors limiting oilseed rape yields and the main cultural practices connected with these limiting factors in organic farming.

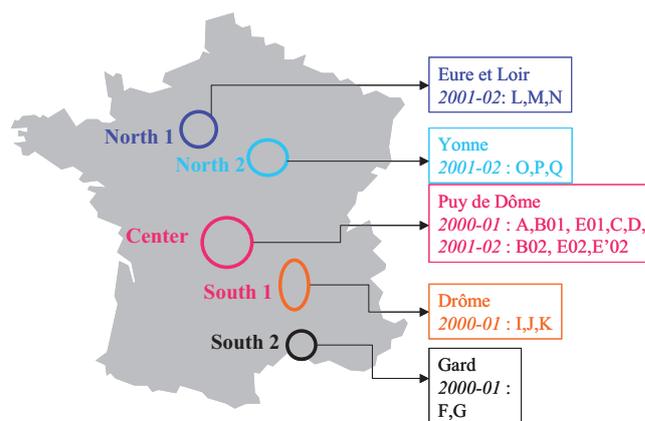
## 2. MATERIALS AND METHODS

We used a diagnosis method (Meynard and David, 1992; Doré et al., 1997) that has been used on many crops, including oilseed rape (Dejoux et al., 2003). The method involves determining and explaining the relationships between characteristics of the crop such as biomass, yield components and nutrient status, the occurrence of pests, weeds and diseases, and cropping practices, soil characteristics and weather on a farmers' field network. The analysis comprises three stages: (i) identifying the yield components that best explain yield variations; (ii) identifying the environmental conditions and limiting factors that act on these yield components; and (iii) specifying the characteristics of the cropping system, climate and soil that create favourable or unfavourable environmental conditions.

### 2.1. Experimental design

A network of 19 farmers' fields (Tab. I) in four regions with contrasting climatic and soil conditions was studied over a two-year period (Fig. 1). Each field was coded, a letter identifying the farm and a number referring to year. Farms A to E are located in the center of France (Auvergne); fields A01 and A02 are therefore two different fields on the same farm in 2001 and 2002, respectively. Farms F to K are located in southern France (Rhône-Alpes); farms L to M are located near Paris (North 1), and farms O and P are located in the eastern Paris basin (North 2). Field size ranged from 1 to 11 ha. We minimised the effects of this heterogeneity on our measurements by studying a part of each field (50 m × 100 m minimum) homogeneous in soil type and crop density. Farmers made their own decisions concerning crop management.

In 14 out of 19 cases, the previous crop was a cereal (Tab. I), and in 15 cases the oilseed rape crop was sown after August 10th (Tab. I). In our field network, oilseed rape was sometimes preceded by cereals other than wheat, such as triticale, or legumes, such as pea (farms A and B), if organic manure



**Figure 1.** Location of the 19 fields according to the year and the region of France (Center, North 1 – west of Paris – and North 2 – south-east of Paris –, South 1 – south of Lyon – and South 2 – near Montpellier) and the name of the *département*.

was not readily available. The oilseed rape crop always preceded wheat in the rotation. Most farmers applied manure before sowing (two farmers spread manure before sowing of the preceding crop) and applied no nitrogen fertiliser or manure in spring. No mechanical weeding was carried out in about half the fields (10 out of 19).

### 2.2. Measurements and observations

**Plants:** On each plot, whole plants were sampled at four different times: (i) in early winter, before winter drainage and the occurrence of low temperatures (early November in northern France and early December in southern France), (ii) in late winter (end of January in the south and mid-February in the north), (iii) early flowering (Sylvester-Bradley (1985) – Growth Stage 4.5 – beginning of April), and (iv) pod filling and most seeds green (Growth Stage 6.3 – beginning of June). On each occasion samples were taken from eight (2001) or six (2002) microplots of 0.5 m<sup>2</sup>. The plants were counted and the roots separated from the aerial parts after washing. Dry biomass (after 48 h of drying at 80 °C) and total nitrogen content of green aerial parts and tap roots (Dumas method) were determined for each microplot sample. We calculated the nitrogen nutrition index (NNI; Lemaire et al., 1997) as the ratio between the nitrogen content of the aerial parts of the plant and critical nitrogen content, using the reference values of critical N content for oilseed rape proposed by Colnenne et al. (1998). The numbers of branches, flowers and fertile pods per plant were counted on 15 randomly chosen plants per microplot at the pod-filling stage. The crop was harvested with a combine harvester, and yield was estimated on two plots of 150 m<sup>2</sup> to 400 m<sup>2</sup>. Moisture content and mean grain weight were determined in a sub-sample of 500 g of grain. The number of grains per m<sup>2</sup> was estimated from yield and mean grain weight.

**Soil:** Soil and subsoil mineral nitrogen contents were determined by colorimetry after extraction in a solution of 1 N KCl, on the day of sampling. A sample from the 0–30 cm layer from

**Table I.** Main cultural practices in the fields of the network; mineral nitrogen content was calculated from the mineral and organic nitrogen content of fresh manure and the amount of manure spread.

Farm fields	Soil management before sowing	Soil type (soil depth – cm)	Crop preceding WOSR	Cultivar	Sowing date	Plant density at emergence (per m <sup>2</sup> )	Organic manure spread before sowing (date, type, amount)	Mineral and organic nitrogen available in the organic manure spread (kg/ha)*	Mechanical tools used for weeding (number of times)
A <sub>01</sub>	Shallow soil tillage	Sa (60)	Pea	Navajo	21/08/2000	64	0		Weed harrow (2)
B <sub>01</sub>	Shallow soil tillage	SaC (90)	Pea	Navajo	21/08/2000	77	0		Weed harrow (2)
B <sub>02</sub>	Shallow soil tillage	SaC (60)	Pea	Pollen	27/08/2001	45	7/08/2001 20 t/ha pig manure	13.5 400	Weed harrow (2)
C <sub>01</sub>	Shallow soil tillage	Csi (90)	Barley	Navajo	16/08/2000	67	09/1999 10 t/ha compost of cowshed manure		Weed harrow (1)
D <sub>01</sub>	Shallow soil tillage	Csa (90)	Barley	Navajo	16/08/2000	66	09/1999 10 t/ha compost of cowshed manure		Weed harrow (1)
E <sub>01</sub>	Ploughing	Csi (120)	Winter wheat	Navajo	26/08/2000	80	13/08/2000 3 t/ha compost of cowshed manure		Weed harrow (2)
E <sub>02</sub>	Shallow soil tillage	Csi (120)	Winter wheat	Pollen	8/09/2001	65	29/07/2001 600 kg/ha organic fertiliser	54 398	Hoeing machine (1)
E'02	Shallow soil tillage	Csi (120)	Winter wheat	Pollen	25/08/2001	67	29/07/2001 600 kg/ha organic fertiliser	54 398	–
F <sub>01</sub>	Ploughing	SiSa (60)	Durum wheat	Constant	26/09/2000	70	15/09/2000 12 t/ha compost of fowl manure		–
G <sub>01</sub>	Ploughing	SiSa (60)	Durum wheat	Constant	26/09/2000	110	15/09/2000 6 t/ha compost of fowl manure		–
I <sub>01</sub>	Ploughing	SaSi (40)	Barley	Navajo	25/08/2000	72	10/01/2001 organic fertiliser		–
J <sub>01</sub>	Ploughing	SaSi (90)	Fallow	Navajo	25/08/2000	76	10/01/2001 organic fertiliser		–
K <sub>01</sub>	Ploughing	SaSi (90)	Fallow	Colosse	10/08/2000	50	? 6 t/ha compost of fowl manure		–
L <sub>02</sub>	Ploughing	SiC (120)	Winter wheat	Pollen	23/08/2001	48	3/08/2001 2.5 t/ha compost of fowl manure	8 70	Hoeing machine (1)
M <sub>02</sub>	Ploughing	SiSa (60)	Pea/triticale	Pollen	5/09/2001	47	3/08/2001 20 t/ha compost of goat manure	33 560	–
N <sub>02</sub>	Ploughing	SiC (120)	Triticale	Pollen	3/09/2001	43	2/08/2001 40 t/ha compost of horse manure and plant residues	18.5 544	–
O <sub>02</sub>	Ploughing	SiC (30)	Triticale	Pollen	8/08/2001	53	29/07/2001 18 t/ha compost of cowshed manure	109 531	–
P <sub>02</sub>	Shallow soil tillage	SiSa (30)	Wheat	Pollen	10/08/2001	104	8/08/2001 25 t/ha compost of fowl manure	10 512	–
Q <sub>02</sub>	Shallow soil tillage	SiSa (90)	Barley	Pollen	23/08/2001	98	26/07/2001 20 t/ha compost of horse manure	11 610	Hoeing machine (1)

\* Analyses of organic manures were not carried out in the first year.

Shallow tillage: chisel or cover crop.

Si: silt; Sa: sand; C: clay. Characteristics of soil were encoded on the basis of texture analysis.

each field was analysed by the INRA laboratory in Arras: to determine particle size and chemical composition: assimilate P – Olsen –, exchangeable Mg and K, total carbon and nitrogen, CaCO<sub>3</sub>, CEC and pH. Rooting depth was determined from observations of auger holes. Soil structure was observed on soil profiles to a depth of 40 cm, using the method proposed by Gautronneau and Manichon (1987).

**Manure:** In the second year, a 500-g sample of fresh organic manure was analysed by the INRA laboratory in Arras to determine total nitrogen and carbon content and mineral nitrogen content. From these data and from the amount of manure applied we calculated organic and mineral nitrogen availability in the soil, based on these measurements and the amount of manure spread (organic and mineral) (Tab. I).

**Weeds:** Weed infestations were assessed on the microplots used for plant sampling, on the same dates. We identified species present and counted the number of plants of each species. We determined total aerial dry biomass of all weeds and total nitrogen content of the aerial parts of the plant for each sample (Dumas method). Two indicators of weed competition were calculated: (1) the relative weed biomass ratio = DM weeds/(DM weeds + DM crop), where DM is Dry Matter as used by Lutman et al. (1996); and (2) the relative weed nitrogen ratio = QN weeds/(QN weeds + QN crop), where QN is Quantity of Nitrogen in the plants. Other indicators included weed species, density of each species, total density of weeds and the type of weed with the highest density. Weeds were classified into types on the basis of three criteria: monocotyledon or dicotyledon, emergence period and height relative to oilseed rape. Seven types of weeds were identified depending on height relative to oilseed rape and period of emergence, similar to Primot et al. (2005).

**Pests and diseases:** We estimated crop damage due to pests and diseases in samples of 15 randomly collected plants per microplot. In autumn, monitoring focused on aphids, larvae of the root maggot (*Delia radicum*) and cabbage stem flea beetle (*Psylliodes chrysocephala*). In late winter, we counted the number of plants on which larvae of cabbage winter stem weevils (*Ceutorhynchus picitarsis*) were present and, at flowering, we counted the number of plants on which larvae of rape stem weevil (*Ceutorhynchus napi*) were present. Two indicators were used for the pollen beetle: the proportion of plants with larvae and the proportion of short peduncles without pods, commonly known as 'blind stalks'. At flowering, we determined the proportion of plants with pollen beetle larvae by dissecting each bud and flower of 10 plants randomly chosen from the same microplots as used for the other measurements. At the pod-filling stage, we estimated crop damage caused by spring insects. We counted the number of blind stalks on 10 randomly sampled plants per microplot. This measurement provided information about bud abortion linked to the incidence of pollen beetle damage (CETIOM, 1994). For pod midges and seed weevils, we counted, at the pod-filling stage, the number of pods that had turned yellow and were open at the base of the peduncle on a sample of 10 plants. Stem canker (*Leptosphaeria maculans*) damage was estimated at the pod-filling stage and a score from 1 to 6 was attributed

according to the degree of rot on a collar cut (Aubertot et al., 2004). The occurrence of *Leptosphaeria maculans* in autumn was assessed by counting the number of plants with at least one leaf lesion. The incidence of other diseases, such as powdery mildew, was also determined in autumn and the incidence of *Sclerotinia* at the G4 stage: we determined the number of plants with at least one leaf lesion in autumn or with at least one stem lesion at the G4 stage.

**Weather conditions:** For each field, the nearest meteorological station from either the Meteo France network or the INRA network was chosen. Daily global radiation, temperature, Penman Potential Evapotranspiration (PPET) and rain were recorded. The number of days without rain and the number of days with minimum temperature below 0 °C were calculated for each field for four periods of development: sowing – early winter; early winter-late winter; late winter-flowering; flowering-harvest. In order to have an indicator of water stress, we calculated the sum of the daily differences between rain and ETPP.

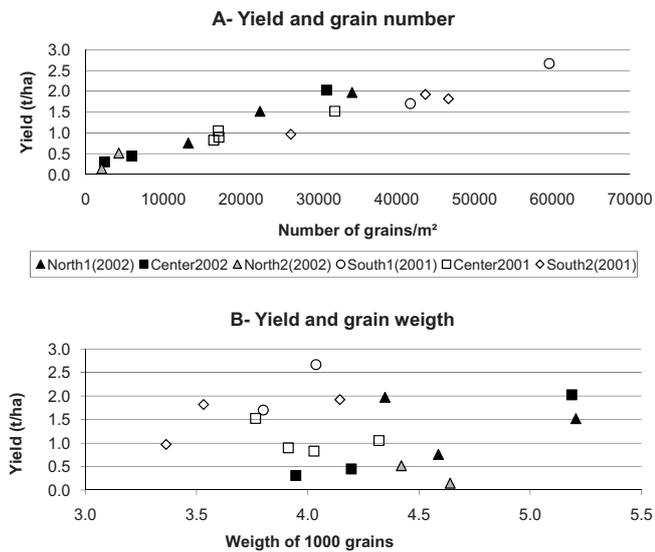
### 2.3. Statistical analysis

We assumed a normal error distribution for continuous variables such as dry biomass and applied standard analysis of variance procedures. Proportions, such as the proportion of plants attacked by rape stem weevil, were analysed after an arcsin√ transformation to stabilise variance between groups. The relationships between yield, yield components and nitrogen status were determined by linear regression. A multiple linear regression procedure was used to describe yield components as a linear combination of the various indicators of limiting factors. A number of indicators of limiting factors were found to be correlated: crop biomass, nitrogen uptake by weeds or the crop and relative weed biomass or nitrogen ratio. These variables were therefore not included in the same model. Parsimonious models retained only factors for which F values were significant at the 0.1 level using a stepwise procedure. All analyses were done in S+.

## 3. RESULTS AND DISCUSSION

### 3.1. Variations in yield and yield components

Yield was highly variable (range 0.14–2.67 t.ha<sup>-1</sup>, mean of 1.19 t.ha<sup>-1</sup>) in this network of farmers' fields. Yields were highest in North 1 and gross margins for the highest yields were similar to those for organic wheat, which may be considered to perform well. Yields were lowest in Bourgogne and highest in the south of France (Fig. 2). The key question therefore relates to why yields are so low in some fields, especially as farmers obtaining such yields often decide not to continue organic oilseed rape production. Most of the farmers in this network had little experience of organic farming. Most previously grew oilseed rape in a conventional system and had little modified their cultural practices.



**Figure 2.** Relationship between yield and its components (A): number of grains/m<sup>2</sup> and (B): weight per grain. One point represents the mean of the two plots for yield measurements. White points and dashed regression line represent results for the first year. Black points and solid regression line represent results for the second year.

In both years, yield depended more strongly on the number of grains.m<sup>-2</sup> ( $P < 0.001$  and  $r^2 = 0.97$ ) than on thousand-grain weight (Fig. 2A). In both years, the yield components' number of branches.m<sup>-2</sup>, number of flowers.m<sup>-2</sup>, number of pods.m<sup>-2</sup> and number of grains.m<sup>-2</sup> were highly correlated (min  $r^2 = 0.80$  and max  $r^2 = 0.94$ ; data not illustrated). This result indicates that the limiting factors affecting yield occurred mainly during the development of grain number. In both years, the high correlations between the yield components suggested that the variations in the number of grains were related to the variations in the number of branches, which indicates very early limiting factors (before branching).

## 3.2. Characteristics of the environmental status and biotic limiting factors

### 3.2.1. Weather over the two years and in the various regions

Weather conditions varied with location, with particularly large differences between the center and the south of France. Climatic conditions were similar in North 2 and central regions in the second year. Winter temperatures fell below 0 °C on 14 days in the south: in contrast, they were sub-zero on 73 days in the center and 68 days in North 2. Frosts may have occurred during flowering in North 2 and the center. The average temperature in the second year was lower than in the first in the center of France, with lower minimum temperatures (-15 °C in the second year and -10 °C in the first). The water stress was also more severe in 2002 than in 2001 in this region.

### 3.2.2. Nitrogen nutrition

The nitrogen nutrition index (NNI) varied between fields, ranging from 0.40 to 1.2 in early winter (Tab. II), and tended to increase over the winter, reaching 0.6 to 1.3 in late winter. Thereafter, it drastically decreased until flowering, ranging from 0.2 to 0.75. In early winter, 3 of 19 fields had a NNI below 0.5, whereas during flowering, 15 of the 19 fields had a NNI below 0.5. High levels of nitrogen uptake by the crop were often associated with high NNI in early winter, except for fields N02 and E02 (significant regression between NNI and nitrogen uptake;  $P < 0.01$ ;  $r^2 = 0.28$  with these two fields and 0.67 without these fields). The mineral nitrogen content of the soil measured in early winter exceeded 60 kg.ha<sup>-1</sup> in only one case (113 kg.ha<sup>-1</sup> in E02). The mean mineral N content of the network did not vary significantly over the crop cycle in a given field: 44 kg.ha<sup>-1</sup> in early winter, 47 kg.ha<sup>-1</sup> in late winter and 46 kg.ha<sup>-1</sup> during flowering (Tab. II). Nitrogen uptake in weeds was variable, ranging from 0.2 kg.ha<sup>-1</sup> to 50 kg.ha<sup>-1</sup>, and tended to be higher if the levels of nitrogen absorption by the crop were low (data not shown). However, the relationship between nitrogen uptake by weeds and by the crop depended on weed type. For example, in the fields E'02 (center 2002) and M02 (North 2), nitrogen uptake in the crop reached 95 kg.ha<sup>-1</sup>, while nitrogen in weeds reached 3 kg.ha<sup>-1</sup> for field M02 and 17 kg.ha<sup>-1</sup> in field E'02. These two fields differed mainly in the type of weeds (Tab. III).

### 3.2.3. Weed competition

Weed density was highly variable (from 18 to 544 plants.m<sup>-2</sup>, Tab. II). In 5 of the 19 fields the main weeds in early winter were volunteers of the preceding wheat or barley crop. In most of these cases, the density of volunteers did not decrease (Tab. III). *Geranium dissectum* occurred in only one field, whereas *Alopecurus myosuroides*, *Sonchus asper* and brassicas such as *Sinapis arvensis* and *Raphanus raphanistrum* occurred in at least two fields. *Alopecurus myosuroides* was the weed with the highest density. In our study, the fields with the lowest yields contained cereal volunteers (type 1 of our classification, detailed in Primot et al., 2005), *Galium aparine* (type 5), *Alopecurus myosuroides* (type 2) and *Sinapis, wild radish* (type 7). The field with the highest yields contained *Mercurialis annua* (type 3). Lutman et al. (1995) have pointed out competitive and not competitive weeds. The authors showed that the types 5 and 7 were rather competitive and that type 6 was not competitive, which is partly in accordance with our study.

The weed biomass ratio was not necessarily high in fields with high weed density: for example, in fields F01, I01, K01 and L02, weed density varied from 118 to 128 plants.m<sup>-2</sup> regardless of the measurement period, whereas the relative weed biomass ratio varied from 0.05 to 0.2. It can also be noticed that the weed biomass ratio in early winter was related to NNI at the flowering stage (data not illustrated;  $r^2 = 0.68$ ).

These different indicators of weed competition (the relative ratio of weed dry biomass, the relative ratio of weed nitrogen and weed density, and weed density by type) must be

**Table II.** Distribution of nitrogen status of the crop (NNI), weed density, biomass nitrogen and weed dry biomass, and disease incidence and gravity in three different periods.

period		min	mean	max
Early winter	NNI	0.4	0.8	1.2
	nitrogen in soil (kg.ha <sup>-1</sup> )	16.0	44.3	113.5
	weed biomass (t.ha <sup>-1</sup> )	0.0	0.4	1.3
	weed density (plant.m <sup>-2</sup> )	21.0	102.5	357.3
	weed ratio of biomass	0.0	0.2	0.6
	nitrogen accumulated in weeds (kg.ha <sup>-1</sup> )	0.20	11.58	47.00
	proportion of plants with phoma lesion	0.00	0.18	1.00
Late winter	NNI	0.6	0.9	1.3
	nitrogen in soil (kg.ha <sup>-1</sup> )	12.3	47.8	100.5
	weed biomass (t.ha <sup>-1</sup> )	0.0	0.4	1.6
	weed density (plant.m <sup>-2</sup> )	10.0	120.4	544.0
	weed ratio of biomass	0.0	0.2	0.7
	nitrogen accumulated in weeds (kg.ha <sup>-1</sup> )	0.00	9.94	28.12
Flowering	NNI	0.2	0.4	0.7
	nitrogen in soil (kg.ha <sup>-1</sup> )	16.7	46.6	101.0
	weed biomass (t.ha <sup>-1</sup> )	0.1	0.9	2.7
	weed density (plant.m <sup>-2</sup> )	18.0	83.1	295.5
	weed ratio of biomass	0.0	0.2	0.8
	nitrogen accumulated in weeds (kg.ha <sup>-1</sup> )	0.87	14.5	50.7
	proportion of plants with sclerotinia	0.00	0.02	1.00
	gravity score of stem canker	0.00	0.7	2.9

discussed a little. The first of these indicators has been used to assess weed competition in previous studies (Lutman et al., 1996, 2000). Lutman et al. (2000) showed that yield loss predictions based on relative weed dry weight were more accurate than those based on weed density. The relative ratio of weed nitrogen has never been used before and serves as an indicator of competition with weeds for nitrogen.

### 3.2.4. Insect damage and disease

The incidence of cabbage stem flea beetle was very variable and depended on the region, with levels of attack particularly high in the south (Tab. IV; 60 and 100% of plants with at least one larva). In contrast, no cabbage stem flea beetle was detected in the north. Root maggot attacks were systematically more severe in the center than in other regions: in this region, we observed symptoms of root maggot attacks on more than 20% of plants in both years (Tab. IV). Cabbage stem flea beetle and root maggot were the most frequently detected autumn insects at field level.

The rape stem weevil (*C. napi*) was the most frequently detected in 10 of the 19 fields, with more than 40% of plants attacked (Tab. IV). In both years, attacks were most severe in the center (in 2 of 4 fields, 60% of plants had symptoms in 2001 while in 2002, all fields were attacked and 100% of plants displayed symptoms). Severe attack of aphids was observed only in one field – C01 – in 2001. Pollen beetles and pod midges caused more severe damage in the second year than in the first. It was the case in the north and center of France, where more than 30% of flowers aborted because of pollen beetle attacks in five of the six fields. In 2001, the number of plants with at least one pollen beetle larva exceeded 50% in eight of 10 fields

(data not shown). However, the proportion of flowers aborted due to pollen beetle attack did not exceed 25%.

Disease incidence was very low: stem canker (*Lep-tosphaeria maculans*) attacked 20% of plants in the first year and 50% in the second year, but the disease score did not exceed 2.9 out of 9 (Tab. II).

### 3.2.5. Soil structure

In most of the fields studied, with the notable exception of field Q02, the soil was not compacted and the regular density of roots over the three soil layers demonstrated that soil structure did not affect the absorption of minerals and water by the crop. In contrast, the soil in field Q02 had a coarse structure, with a high proportion (100% and 70 % of soil volume in the first two layers, respectively) of highly compacted clods. This structure strongly impeded root growth and functioning.

### 3.3. Identification of the limiting factors of crop biomass, yield components and yield

We carried out several stepwise regression analyses on crop biomass and yield components at each stage: crop biomass in early and late winter, number of flowers.m<sup>-2</sup> at flowering, number of branches.m<sup>-2</sup> and number of pods.m<sup>-2</sup> at the pod-filling stage, and number of grains.m<sup>-2</sup> at harvest. Relationships between these variables and possible limitations due to pests and climate during the crop cycle were investigated (Fig. 3). This method permitted us to identify and rank the major limiting factors occurring in an organic system, which has never been done.

**Table III.** Main weeds observed (common name and *Latin name* in each farm field in early winter and at flowering).

Farm field	Early winter	Flowering (F2)
	Main weeds	Main weeds
A01	Meadow cranesbill <i>Geranium dissectum</i>	Meadow cranesbill <i>Geranium dissectum</i>
B01	Common sow thistle <i>Sonchus asper</i>	Groundsel <i>Senecio vulgaris</i>
B02	Common sowthistle <i>Sonchus asper</i>	Common field speedwell <i>Veronica arvensis</i>
C01	Barley	Barley
D01	Barley	Barley
E01	Wheat	Wheat
E02	Wheat	Wheat
E'02	Wheat, cleavers <i>Galium aparine</i>	Cleavers <i>Galium aparine</i>
F01	Annual mercury <i>Mercurialis annua</i>	Red shank <i>Polygonum persicaria</i>
G01	Annual mercury <i>Mercurialis annua</i>	Red poppy <i>Papaver rhoeas</i>
I01	Wild chamomile <i>Matricaria recutita</i>	Violet <i>Viola arvensis</i>
J01	Chick weed <i>Stellaria media</i>	Violet <i>Viola arvensis</i>
K01	Common foxtail <i>Alopecurus myosuroides</i>	Lady's mantle <i>Aphanes arvensis</i>
L02	Perennial ryegrass <i>Lolium perenne</i>	Perennial ryegrass <i>Lolium perenne</i>
M02	Red poppy <i>Papaver rhoeas</i>	Red poppy <i>Papaver rhoeas</i>
N02	Wild mustard <i>Sinapis arvensis</i>	Common foxtail <i>Alopecurus myosuroides</i>
O02	Common foxtail <i>Alopecurus myosuroides</i>	White clover
P02	White clover Wild radish <i>Raphanus raphanistrum</i> , Common field speedwell <i>Veronica arvensis</i>	Wild chamomile <i>Matricaria recutita</i> Common foxtail <i>Alopecurus myosuroides</i>
Q02	Common foxtail <i>Alopecurus myosuroides</i>	Common foxtail <i>Alopecurus myosuroides</i>

### 3.3.1. Climatic factors

In early and late winter, the proportion of variance in crop biomass accounted for by climatic conditions (number of cold days, water stress and number of days without rain) did not exceed 10% in early winter and 5% in late winter. During flowering, while the number of flowers.m<sup>-2</sup> was slightly affected by the number of cold days, the number of pods.m<sup>-2</sup> was affected by water availability for the plant: soil depth and number of days without rain (Fig. 3A, B).

### 3.3.2. Insect damage and disease

In early and late winter the proportion of the variance accounted for by flea beetles did not exceed 10% in early winter and cabbage stem weevils did not appear to be significant in

late winter. The percentage of plants with at least one phoma lesion on leaves and NNI in early winter were significant in regression analysis (probability not shown) but the proportion of the variance accounted for by this factor was small (Fig. 3A). During flowering, the only pest accounting for more than 5% of the variance throughout the crop cycle was rape stem weevil on the number of branches and pollen beetle on the number of pods.m<sup>-2</sup>, whereas the percentage of plants with *sclerotinia* and the gravity score of stem canker did not account for more than 1.5% of the variance (Fig. 3C). Very few studies have reported the impact of pollen beetles on yield losses (Nilsson, 1994), mainly because of the capability of the crop to compensate for the abortion of some flowers. It may explain why the pollen beetle was not selected to explain the number of grains.m<sup>-2</sup> (Fig. 3D).

### 3.3.3. Weed competition and nitrogen

In early and late winter, total crop biomass was significantly affected by weeds. The relative weed nitrogen ratio, weed biomass, weed density and the main type of weed were identified as significant in stepwise regressions. All indicators of weed competition had a negative coefficient in the linear regression (data not shown). These indicators of weed competition together accounted for 38.9% (Fig. 3A) of the variance in early winter and 40% in late winter. The type of weed, characterised in terms of period of emergence and height with respect to the crop, affected the various yield components and had a significant effect early in the crop cycle. Various studies on the competitive effects of volunteer cereals on oilseed rape demonstrated the importance of crop vigour in determining crop competitiveness (Lutman and Dixon, 1991). The results obtained in fields C01, D01, E02 and E'02, which had high volunteer densities, confirmed these results and were in accordance with Lutman et al. (1995).

At flowering and before harvest, nitrogen and weeds accounted for significant proportions of the variation in numbers of branches, flowers and pods.m<sup>-2</sup> (Fig. 3B, C). Plant nitrogen uptake accounted for an increasing proportion of variation: 9% for the number of branches.m<sup>-2</sup>, 29.5% for the number of flowers.m<sup>-2</sup> and 58% for the number of pods.m<sup>-2</sup>. However, the hierarchy of these limiting factors (nitrogen and weeds) in those periods differed slightly from that before the winter. Indeed, nitrogen status of the crop at flowering largely accounted for the numbers of branches and of flowers per m<sup>2</sup>, whereas weed dry biomass and nitrogen uptake by weeds accounted for no more than 2% of the variance of flowers.m<sup>-2</sup> and 15% of variance of pods.m<sup>-2</sup>. In both years, grain number.m<sup>-2</sup> was strongly correlated with the amount of nitrogen absorbed in early winter or at the pod-filling stage (data not shown).

The two main factors affecting growth and yield components - crop nitrogen status and the weed population - were interdependent. Indeed, if NNI in early winter was high (greater than 0.7), then the weed biomass ratio at flowering tended to be low. In contrast, if NNI in early winter was low (less than 0.7), then the weed biomass ratio at flowering tended to be high. Figure 4 illustrates this significant relationship between

**Table IV.** Number of fields in which damage due to the pest cited occurred. Presence of or damage due to *Psylliodes chrysocephala* L. and *Delia radicum* L. was measured in early winter on a sample of 90 plants (15\*6 microplots). Presence of or damage due to *Ceuthorhynchus picitarsis* was measured in late winter and the presence of or damage due to *Ceuthorhynchus napi* + *Brevicoryne brassicae* L. was measured at flowering on a sample of 90 plants. For *Meligethes aeneus*, at the pod-filling stage, the number of blind stalks on 10 randomly sampled plants per microplot was counted. For pod midges and seed weevils, we counted, at the pod-filling stage, the number of pods that had turned yellow and were open at the base of the peduncle on a sample of 10 plants.

Autumn insects	0–20% of plants attacked	20–60% of plants attacked	60–100% of plants attacked
Cabbage stem flea beetle ( <i>Psylliodes chrysocephala</i> L.)	9 fields	5	5
Root maggot ( <i>Delia radicum</i> L.)	10	7	2
Rape stem weevil ( <i>Ceuthorhynchus napi</i> )	17	2	0
Cabbage stem weevil ( <i>Ceuthorhynchus picitarsis</i> )	4	6	9
Aphids ( <i>Brevicoryne brassicae</i> L.)	17	1	1
Spring insects	0–20% of flowers in aborted bloom	20–40% of flowers in bloom aborted	40–60% of flowers in bloom aborted
Pollen beetle ( <i>Meligethes aeneus</i> )	9	8	2
	0–20% of pods with symptoms	20–40% of pods with symptoms	40–60% of pods with symptoms
Pod midges ( <i>Dasineura brassicae</i> )	17	2	0

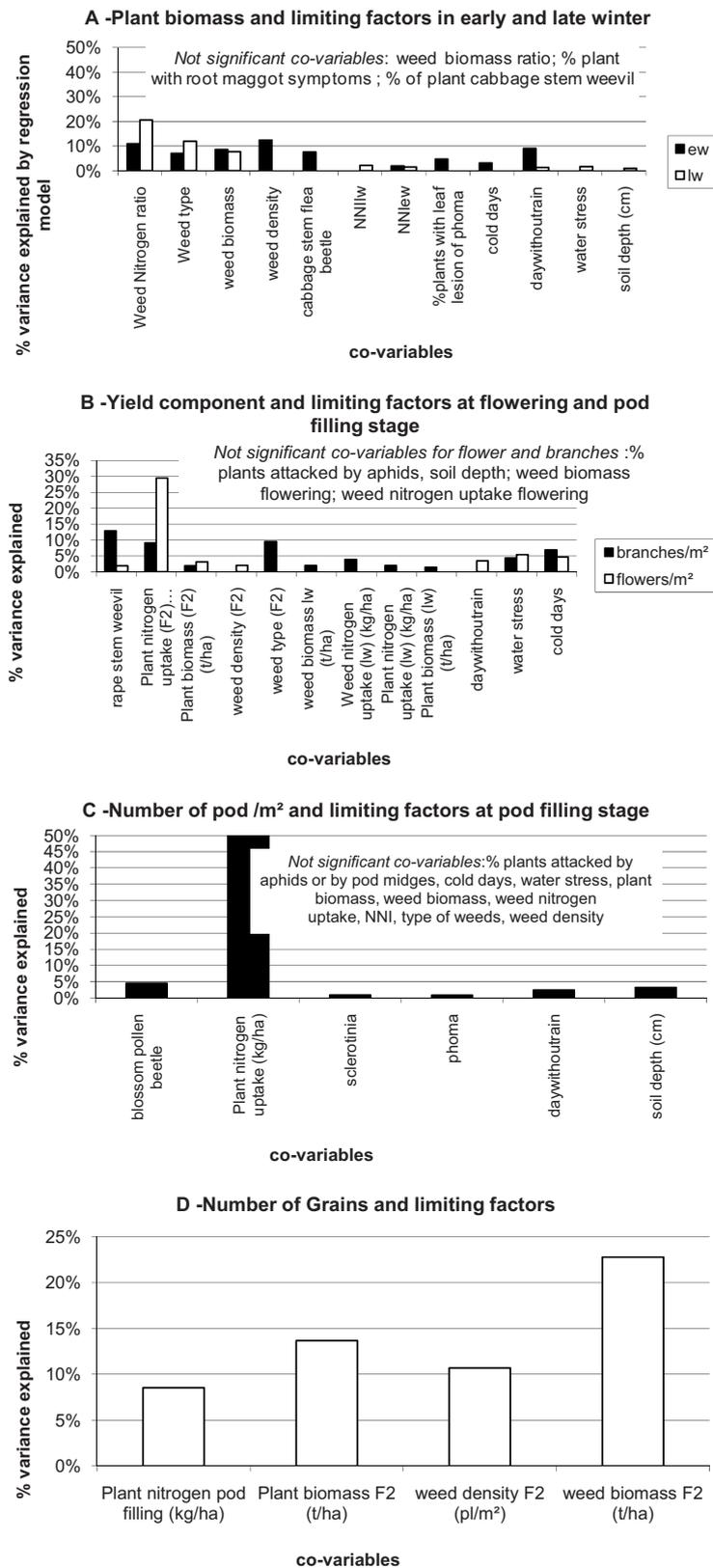
the amount of nitrogen accumulated in the crop during autumn and the weed dry biomass. Primot et al. (2005) pointed out that the threshold of weed biomass that could induce yield loss was 0.15 t.ha<sup>-1</sup>. In our study, before this value of dry weed biomass, the mean value of nitrogen in crops was 98 kg.ha<sup>-1</sup>. Therefore, considering that oilseed rape is able to trap high amounts of nitrogen in soil, it could be concluded that the minimum amount of nitrogen that farmers should spread before sowing, in order to ensure that crops compete with weeds, is around 100 kg/ha.

If we detail the results on weed competition, it can be mentioned that the relative ratio of weed nitrogen before spring had a high and significant effect, suggesting that competition between crops and weeds for nitrogen has an impact on crop growth. This is consistent with the low values of the nitrogen nutrition index (< 0.7) obtained in half of the fields in early winter and in almost all fields at flowering. In our results crops with nitrogen nutrition index values greater than 0.7 were in competition with a lower biomass of weeds, even if weed densities were high. Ferré et al. (2000) and Dejoux et al. (1999) found that high levels of nitrogen uptake during autumn were associated with a large increase in biomass and leaf area index, resulting in a decrease in weed growth and density. Our results demonstrate that this specific trait is important in organic farming. High levels of nitrogen uptake in the autumn make the crop more competitive against weeds throughout the crop cycle, due to an early smothering effect, resulting in an early decrease in weed density and long-term positive effects

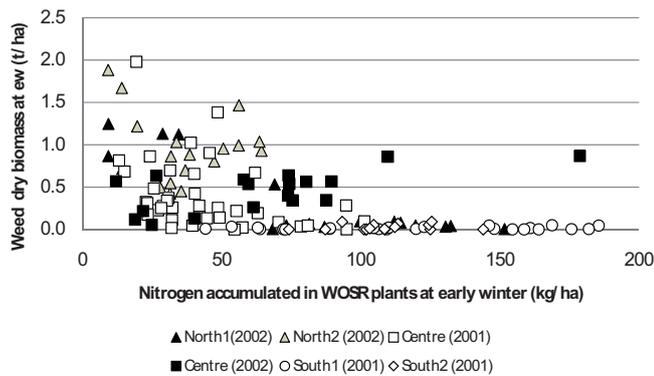
on crop growth, with no weed seed production, as was observed by Ferré et al. (2000). Moreover, the proportion of the variance accounted for by weed indicators was lower for the number of flowers and grains.m<sup>-2</sup> than for early biomass or the number of branches. This suggests that the critical period of competition for the crop occurred very early in the crop cycle, essentially before winter. Welsh et al. (1999) confirmed that the control of weed emergence in organic wheat crops was the most important at the beginning of the crop cycle.

The results in early and late winter on the effects of weed competition on the number of branches.m<sup>-2</sup> also showed that competition with weeds explained the results for branching, but that the uptake of nitrogen of the crop was more relevant in spring. Those results suggested that competition with weeds before spring resulted in low nitrogen availability for the crop during autumn, but also during the period of re-growth and branching, which might have had consequences on the number of flowers (Colnenne et al., 1999; Maillet, 1992), and consequently on the number of grains.m<sup>-2</sup>.

All these results permitted us to conclude two main results: (i) during autumn and winter, weed competition (weed biomass, the weed or nitrogen ratio, and weed density) and nitrogen uptake were the main factors accounting for the high variability in oilseed rape biomass and the number of branches.m<sup>-2</sup> and thereafter the number of grains; and (ii) despite the high values of insect occurrence in some fields (Tab. IV), they explained the yield loss in low proportion except for pollen beetle and rape stem weevil. In conventional



**Figure 3.** Results of stepwise regressions on the various yield components throughout the crop cycle: in early and late winter (A) during flowering and the pod-filling stage (B) or for the number of pods.m<sup>-2</sup> (C) or for the number of grains.m<sup>-2</sup> (D). Ew and lw mean early winter and late winter. F2 corresponds to the flowering stage. NNI is the nitrogen nutrition index.



**Figure 4.** Relationship between nitrogen accumulated in plants and nitrogen accumulated in weeds for each region in early and late winter and at flowering. One point represents the result of a microplot.

systems, diseases, such as *Phoma* and *Sclerotinia*, are often responsible for high yield losses (Merrien and Pouzet, 1988), which is rather different from organic systems.

### 3.4. Effect of crop management and environmental conditions on limiting factors

Since weed competition and nitrogen appeared in the previous section to be the main limiting factors of yield, we investigated here the effects of crop management on the indicators of weed competition, and nitrogen uptake and deficiencies.

#### 3.4.1. Date and density of sowing, soil tillage and weeding

The various indicators of weed competition in early winter were largely accounted for by plant density, the previous crop or soil management before sowing, and in a lower proportion, sowing date (Tab. V). The date of sowing had a significant effect only on the weed dry biomass ratio (Tab. V). This effect has been shown to have a major effect on plant growth at early stages (Dejoux et al., 2003) and on the competitiveness of the crop (Whytock, 1993; Ferré et al., 2000). There is an interaction between sowing date and soil nitrogen availability on plant growth during autumn (Dejoux et al., 1999; Ferré et al., 2000). Those studies may explain the sole effect of sowing date on the weed dry biomass ratio and may account for the diverse results observed in our field network. The analysis of covariance (Tab. V) also showed that nitrogen availability in the soil at sowing may have affected weed density. Increases in soil nitrogen content tended to decrease weed biomass, but this relationship may have depended on weed type and density (Tab. III: see Fields E'02 (center 2002) and M02 (North 2); Fig. 3A). Our experimental design did not allow us to test whether there was an interaction between weed type and nitrogen availability, but this is likely to have been the case and has already been observed in wheat (Jørnsgård et al., 1996), potato (Delden et al., 2002) and sugar beet (Paolini et al., 1999).

The effects of sowing date and nitrogen availability on weed competition are consistent with the similar effects on crop nitrogen deficiencies and nitrogen content in soil. Analysis of covariance showed that sowing date, soil management and the quantity of organic manure spread were correlated with the NNI, nitrogen uptake by plants and soil nitrogen content three weeks after sowing (Tab. V): early sowing date, high organic manure application and ploughing were related to high crop NNI, high aerial crop biomass and low nitrogen uptake by weeds.

Oilseed rape plant density had a significant effect on dry weed biomass in early winter, but this effect did not persist until flowering (data not shown). This was not observed in a previous diagnosis study on conventional oilseed rape (Dejoux, 1999), which may be due to the higher weed density and larger range of weed types in our study. Moreover, the effect of crop density might also interact with the type and the density of the weeds in competition, as it was observed in wheat (Angonin et al., 1996).

Although few studies have dealt with the effect of soil management on weed emergence in oilseed rape, shallow tillage has been shown to result in a larger weed seed emergence in corn and winter wheat crops than ploughing (Barberi and Lo Cascio, 2001; Feldman et al., 1997). Our results confirm these studies. Moreover, the effect of soil tillage on the preceding crops could have consequences on soil structure. It was the case in field Q02, which exhibited a compacted structure, which may explain the poor uptake of available nitrogen by the crop in this field. The massive, compact soil structure observed in field Q02 strongly impeded root growth and functioning.

Mechanical weeding was significantly related to low weed biomass and a low dry weed biomass ratio, but was not related to weed density.

Rape stem weevil was selected in stepwise regressions, and contributed to high variance. Pollen beetle had a major effect on some fields: the incidence of this insect on the three fields in the North 2 of France varied from 30% to 60% of blooming flowers aborted. A previous study (Valantin-Morison et al., 2007) demonstrated that crop management, including sowing date, soil nitrogen and plant density in particular, has a significant effect on those pests' occurrence. This study also shows the great importance of landscape structures for pests' attack.

#### 3.4.2. Organic fertilisation and crop rotation

In our study, no organic fertiliser was applied during spring, while organic manure was sometimes spread before sowing. It resulted in high nitrogen deficiencies in spring in many fields. According to Colnenne et al. (2002), autumn nitrogen deficiencies generally have no effect on yield and the grain number but nitrogen deficiencies during spring affect the number of flowers (Colnenne et al., 1999). The absence of spring fertilisation in our network could therefore explain the severe impact of autumn and spring deficiencies on yield components (Fig. 3). This absence of spring fertilisation may be due to the high cost of the off-farm nitrogen fertilisers (such as feather meal or guano) generally used for wheat fertilisation (David

**Table V.** Probability (% of variance accounted for) and coefficient of the regression obtained in a co-ANOVA analysis concerning the effects of cultural practices and environment on various indicators of weed competition in early winter and on the nitrogen status of the crop in early winter. Coefficients are not detailed for qualitative variables such as previous crop and type of organic manure.

Environmental status or cultural practices accounting for weed indicators	Weed density (pl/m <sup>2</sup> ) R <sup>2</sup> = 0.27	Weed biomass (t/ha) R <sup>2</sup> = 0.35	Ratio of weed biomass R <sup>2</sup> = 0.62
Amount of nitrogen in soil 3 weeks after sowing (kg/ha)	0.02 (3.1%)	0.04 (2.1%)	0.000 (6.2%)
Plant density (plants/m <sup>2</sup> )	-0.77	-0.0024	-0.0029
Sowing date (Julian days)	0.06 (2.1%)	0.09 (14.9%)	0.034 (1.4%)
	-1.16	-0.0037	-0.0025
	0.73	0.47	0.000 (39%)
			0.0049
Previous crop	0.000 (10.9%)	0.000 (16.5%)	0.000 (6.4%)
Soil management (encoded as shallow tillage 0 and ploughing 1)	0.00 (9.6%)	0.000 (8.2%)	0.000 (7.4%)
Mechanical weeding (utilisation of weed harrow or weed hoe-1- or neither-0-)	-0.98 (1.3%)	-0.0034 (7.1%)	-0.0023 (1.4%)
	-26	0.23	-0.07
	NNI R <sup>2</sup> = 0.54	Nitrogen uptake in plants (kg/ha) R <sup>2</sup> = 0.54	Nitrogen in soil three weeks after sowing (kg/ha) R <sup>2</sup> = 0.21
Sowing date (Julian day)	0.00 (41%)	0.07 (1.2%)	0.002 (5.8%)
	0.013 (7.7%)	0.42 (14%)	2.5
Soil depth (cm)	0.00 (7.7%)	0.00 (14%)	0.94
	-0.096	-23.7	
Soil management (encoded as shallow tillage 0 and ploughing 1)	0.00 (5.7%)	0.00 (24%)	0.49
Quantity of organic manure spread before sowing (t/ha) – see Table I-	0.130 (0.08%)	48.0 (11.5%)	
	0.0007	1.43	0.00 (15%)
			3.9

et al., 2005). Seventeen of the 19 fields were treated with organic fertiliser in autumn. The type of organic manure used seems to be of importance: although only a small amount of organic manure was applied to fields G and K, absorption by the crop in early winter was higher in these fields than in field B02. Oilseed rape is an efficient nitrate-trapping crop, particularly if sown early (Dejoux et al., 2003). Moreover, oilseed rape leaves falling in the autumn and winter can return nitrogen to the soil during spring (Dejoux et al., 2000). This may explain why organic nitrogen applied in autumn to fields F01, G01, L02, J01, M02, K02, B01 and B02 resulted in yields exceeding 1.5 t.ha<sup>-1</sup>.

The farmers' surveys permitted us to point out that the place of oilseed rape in the crop rotation depends on the availability of organic manure, which is the main constraint of organic

farmers. If organic manure is easily available on the farm or exchanges are made with mixed farms, oilseed rape is preceded by cereals (mainly wheat). In such cases, as the crop can return nitrogen to the soil, many farmers aim to replace some grain legumes, such as tick bean (*Vicia faba* L. var. minor Harz), by oilseed rape in the rotation or to introduce oilseed rape into a longer rotation before a winter wheat crop. If organic manure or fertiliser is not available on the farm, oilseed rape is preceded by grain legumes.

#### 4. CONCLUSION

The regional agronomic diagnosis methodology, already tried and tested on several problems in conventional

agriculture, was here adapted to a study of variation in yield in organic systems, where more numerous limiting factors could be observed. A stepwise regression procedure has been used in previous studies on the yield or on the final yield components such as number of grains and protein content (Brancourt-Hulmel et al., 1999; David et al., 2005; Le Bail and Meynard, 2003). In our study, a range of possible limiting factors throughout the crop cycle led us to use a regression procedure for different periods, using the yield components during spring and biomass during autumn as dependent variables. This type of analysis has never been done. David et al. (2005), who used the same diagnostic method on organic winter wheat, also demonstrated that weeds and nitrogen are the main limiting factors. This study also demonstrated that crop densities, type of weeds and soil tillage affect the relationship of the crop with the weeds very early in autumn. From a practical point of view, the results of this study demonstrate that it should be possible to reduce weed problems by ensuring that nitrogen availability is high at sowing and during the autumn. In the organic system, nitrogen availability constitutes a problem; this study provided a key element on the minimum amount of nitrogen that the crop should uptake to compete with the weeds during autumn. With the exception of the deleterious effects of some insects, it should be possible to increase oilseed rape yields in organic systems by limiting competition with weeds for nitrogen early in the crop cycle. Conversely to conventional farms, oilseed rape may not be cultivated in all organic farming systems. Mixed farms and farms with other sources of organic manure could easily adopt this crop as part of their rotation. Moreover, because of autumn fertilisation with organic manure, an environmental assessment of oilseed rape organic crop management should be carried out.

**Acknowledgements:** We are indebted to G. Grandeau, V. Tanneau, B. Fouillen, C. Soin, A. Chauveau, R. Baudoin and E. Castel for their technical help. Y. Ballanger from the Cetiom (*Center technique des oléagineux métropolitains*) provided helpful expertise for the diagnosis of insect damage. We would also like to thank S. Tanis-Plant for editorial advice and T. Doré for his relevant advice. Financial support for this study was provided by the INRA (CIAB) and by the CETIOM. We specially thank R. Reau, L. Quéré, C. Bonnemort and D. Chollet from the Cetiom for their help in finding financial support and in building the farmers' network.

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