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Why are wheat yields stagnating in Europe?

A comprehensive data analysis for France

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Abstract

The last two decades are witnessing a decline in the growth trend of cereal yields in many European countries. The present study analyses yield trends in France using various sources of data: national and regional statistics, scattered trials, results of agroclimatic models using climatic data. Effects in genetic changes through breeding, agronomy and climate are investigated as possible causes. Our results show that genetic progress has not declined but it was partly counteracted, from 1990 on, by climate change which in general is unfavorable to cereal yields in temperate climates because of heat stress during grain filling and drought during stem elongation. We cannot however, from the decade beginning in 2000, rule out agronomic causes, related to policy and economy, in particular the decline of legumes in the cereal rotations, replaced by oilseed rape and to a lesser extent the decrease in nitrogen fertilization.

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1

2 Keywords: wheat yield, genetic progress, climate change, crop management,

3 agroclimatology, crop simulation, France

4

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1 Introduction

2
3 During the second half of the 20th century, cereal yields in Europe have shown a steady
4 growth trend (Calderini and Slafer, 1998) thanks to progress in genetics (mainly an increase
5 in the harvest index) and in the use of inputs for reducing environmental limitations (nitrogen
6 fertilizers, irrigation, pesticides) (Gervois et al., 2008). Climatic effects are discernible as
7 variability around this increasing trend.

8
9 The results are now accumulating, showing that the last two decades are witnessing a
10 decline in this growth trend, even to the point of stagnation, for both wheat and barley in
11 Europe (but also in certain countries on the American continent such as Mexico) and for
12 other major food cereals such as rice in Asia: Calderini and Slafer, 1998; Cassman, 1999;
13 Lahda et al, 2003; Finger, 2008; Kalra et al., 2008; Peltonen-Sainio et al., 2009a, Finger,
14 2010. The turning point is difficult to define precisely but it seems to lie in the period 1992-
15 1995 (Peltonen-Sainio et al., 2009a, Finger, 2010). However this trend does not apply to
16 every country (Lobell et al., 2005), and in 2003 Hafner showed that world production
17 continued to increase. An increase in the year-to-year variability is sometimes mentioned
18 although the results are not significant (Calderini and Slafer, 1998; Peltonen-Sainio et al.,
19 2009b, Finger, 2010).

20
21 Faced with the increasing world food requirements and the limits to the potential for opening
22 up new farmland, this finding is very worrying, and can only aggravate the world food crisis
23 (Calderini and Slafer, 1998; Spiertz and Ewert, 2009). The increase in cereal requirements is
24 due not only to the population increase but also to dietary changes in the high-growth
25 countries such as China and India (Nicolas, 2005; Spiertz and Ewert, 2009). Increase in the
26 agricultural area is limited because there is not much virgin land left to clear, and towns

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1 expand inexorably over farmland because of the population increase. Furthermore one can
2 expect an increase in the use of farmland for non-agricultural activities, which risks
3 exacerbating the world food shortage. Yet the countries affected by the stagnation of yields
4 are exactly those which contribute significantly to the supplies, thanks to their high yield
5 levels (France, Germany, England) as well as the big exporting countries whose advantage
6 lies in their large land area (United States, Australia, Argentina, Canada). This problem,
7 added to the continuing droughts in Australia and the increasing growth of biofuel crops
8 (Spiertz and Ewert, 2009), is responsible for the fall in cereal reserves in 2006, which led to a
9 rapid price increase in 2007.

10
11 The possible causes of this change in the yield trend may be genetic, agronomic or climatic.
12 Political or economic causes (e.g. reunification in Germany, CAP¹ policy) may also be
13 evoked but since they lead to changes in the management of fields as regards choice of
14 species, practices, use of inputs or of soil-crop allocations, they constitute the major
15 determinants of the possible agronomic causes of yield stagnation. Although certain authors
16 suggest that there may be an upper limit to genetic improvement (Calderini and Slafer,
17 1998), others provide evidence that genetic progress has not declined in recent years (Bell et
18 al., 1995; Peltonen-Sainio et al., 2009a). Furthermore, the fact that countries with low yields
19 have also been affected tends to discredit this argument (Hafner, 2003). Agronomic causes
20 are often invoked for European countries, based on the assumption of extensification of
21 practices and a reduction of inputs due to the CAP (Finger, 2008; Peltonen-Sainio et al.,
22 2009a, Finger, 2010) or other environmental policies. Yet there is no tangible support for this
23 hypothesis: Butault (2006), for example, shows that the CAP of 1992 did not lead to any
24 significant changes in terms of inputs, and the slight fall in nitrogen fertilization of about 20 kg
25 N ha⁻¹, mentioned by Peltonen-Sainio et al. (2009a), cannot by itself have been responsible
26 for the observed stagnation in yields. Climate is a cause which is mentioned only marginally

¹ CAP : Common Agricultural Policy

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1 or very locally (for example for cotton in the Sahel by Fok, 1998). However, the harmful effect
2 of the increase in night temperatures on rice yields in Asia seems well established (Lahda et
3 al., 2003; Peng et al., 2004). Lobell and Asner (2003) also demonstrated the adverse effect
4 of high temperatures on maize and wheat yields in the USA. On a regional scale, Kalra et al.
5 (2008) found a relationship between the increase in temperatures and yield stagnation,
6 although the harm could be partially offset by an avoidance strategy including earlier sowing
7 (Kalra et al., 2008; Gate, 2007). In other respects the increase in temperatures can have
8 beneficial effects in northern latitudes as it allows an extension in the arable area (e.g. in
9 Sweden: Holmer, 2008) although Peltonen-Sainio et al (2009b) demonstrated that in the last
10 decade climate has no noticeable effect on yield variability of the main crops in Finland. In
11 the latest report of the IPCC¹ (2007), some signs of the impact of climate change are pointed
12 out for Europe, but are interpreted as being limited and not revealing. In the same time
13 predictive studies, trying to evaluate the reverse relationship between the SRES² emission
14 scenarios and the capabilities to feed the corresponding world population, foresee that even
15 the so-called environmental scenarios (B1 and B2 : Ewert et al., 2005), require some further
16 productivity increase. Such studies take into account the CO₂ effects only (Parry et al., 2004)
17 or additional technical development (Ewert et al., 2005) and show that the more economic
18 the scenario (A1 and A2), the more productive the crops. Such results are not necessarily in
19 agreement with the observed yield trends.

20
21 In methodological terms, the papers mentioned above, when they deal with a national scale,
22 rely on production data and yields are deduced from the production/area ratio; this is
23 especially the case with FAO data though there is not a standard method in all countries
24 (Calderini and Slafer, 1998; Hafner, 2003). It is therefore important that, in the analysis of the
25 results, changes in crop areas are mentioned. In order to understand the causes of yield
26 changes, it is useful to compare several sources of data. For example Peltonen-Sainio et al.

¹ IPCC : International Panel for Climate Change

² SRES : Special Report on Emission Scenarios

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1 (2009a) demonstrate the value of comparing results of genetic and agronomic trials and
2 national statistics to separate genetics, farming practices and extensification. For their part,
3 Kalra et al. (2008) and Lobell et al. (2005) illustrate the use of crop models to test climate
4 impact related hypotheses. The constant trend of increasing yields is traditionally shown by a
5 positive linear regression between yields and the time since the beginning of intensive
6 farming, which was roughly in the 1950s but varied with the country: the 30s in the USA, the
7 50s in Europe, and the 80s in certain Latin American countries (Calderini and Slafer, 1998).
8 However the works of Kumar Boken (2000) and Finger (2010) show that quadratric models fit
9 the trend better than the linear model, revealing a significant inflexion point in the trend.

10

11 In this study we focus on the changes for the yield trends for wheat, a major world staple
12 food cereal, with also an attention to the year-to-year variability. After a look on the
13 importance of wheat yield stagnation on the European scale, we will analyze the causes on
14 the French scale by making use of departmental and local results. Since more than 90% of
15 wheat areas in France are grown with bread wheat, we focus our French analysis on bread
16 wheat. We will use various sources of data (national statistics, scattered trials, results of
17 agroclimatic models) both to support the finding and to investigate its causes. In this way we
18 will analyze successively the genetic, agronomic and climatic causes of the stagnation of
19 French yields. As far as agronomy is concerned, we will examine successively the case of
20 nitrogen, protection against diseases and the effect of the preceding crop, three essential
21 technical components of wheat growing. We will also evoke soil quality.

22

23

24

1. Materials and methods

1.1 Sources of data

The data used for this study are of various kinds and from various sources (Table 1) from national and departmental scales for statistical data to a local level for variety and agronomic trials and climatic data. The presentation of the French results is organized in six geographical sectors of interest for wheat crop: North, Centre, East, West, Southeast and Southwest. We have collected the longest series available (from 9 to 50 years) so as to present significant results.

1.1.1 National and regional statistics

The national data (France, United Kingdom, Germany, Italy, Netherlands, Switzerland and Denmark) for trends in production and agricultural areas come from FAO statistics (<http://www.fao.org> : let us just notice that FAO statistics do not make any distinction between bread and durum wheat). For France, on the regional scale (French Ministry of Agriculture or AGRESTE statistics : <http://agreste.agriculture.gouv.fr>), for each of the six geographical sectors analyzed, three representative departments for the cereal crop were chosen: Nord (59¹), Aisne (02) and Somme (80) for the North sector ; Cher (18), Yvelines (78) and Eure et Loire (28) for the Centre, Yonne (89), Côte d'Or (21) and Saône et Loire (70) for the East ; Gard (30), Vaucluse (84) and Drôme (26) for the Southeast, Côtes d'Armor (22), Ile et Vilaine (35) and Morbihan (56) for the West, and lastly Haute Garonne (31), Gers (32) and Dordogne (24) for the Southwest. The yields are calculated as the ratio of production to the area sown with wheat.

¹ Department administrative number

1 We have also used results of surveys of farming practices for arable crops from the French
2 Ministry of Agriculture or professional organizations such as the National Joint-trade
3 organization for Arable Crops (ONIGC) and ARVALIS-Plant Institute (ARVALIS) for the
4 North, Centre and East sectors. Soil data are provided by the INRA soil service (INFOSOL)
5 as results of the national collection of soil analyses.

6 1.1.2 Scattered trials

7
8 To estimate genetic progress in the bread wheat species, we have used data from 3 sets of
9 reference variety trials at the national level, the oldest of which began in 1970. Two of them
10 were used for evaluating advanced lines (at least the F8 generation) of the INRA breeding
11 program, and the third was carried out by the Permanent Technical Selection Committee for
12 the registration of varieties in the official French catalogue (CTPS). The data analyzed are
13 the mean yields obtained each year on 7-8 (INRA network), or about 20 (CTPS network) trial
14 sites situated in northern France (
15 Table 1). From 1982, the year when fungicidal treatments were introduced into the INRA
16 trials (against the worst fungal diseases of the wheat crop – powdery mildew, brown and
17 yellow rusts, *Fusarium* foot rot, *Septoria* leaf spot), the number of trials was doubled up to
18 give a « treated » (INRA_T) set in parallel with an « untreated » (INRA_{NT}) set. The data
19 available for CTPS network comprise only trials with fungicidal treatments (CTPS_T). All the
20 trials were fertilized to avoid nitrogen limitation. The datasets used were large: 1517, 1185
21 and 922 values of genotypical means for the INRA_{NT}, INRA_T and CTPS_T networks
22 respectively.

23
24 We also used data from two kinds of agronomic trials of the ARVALIS network were also
25 made use of. The « damage » trials, scattered over the whole country, allow the damage
26 caused to the crop by fungal diseases to be calculated by difference between crops treated
27 and untreated with fungicides: the results will be presented as national means. The « farming

1 practices » trials are carried out in several regional centers and aim to estimate the maximum
2 yield obtainable by applying optimal practices as used in intensive agriculture. Results will be
3 presented for three of the sectors analyzed: North, East and Southeast.

4 **1.1.3 Weather data for calculations and modeling**

5
6 We used crop models to assess the effect of the climate on the wheat crop, which allow the
7 effects of various climatic factors to be combined dynamically. To do this, the data from long
8 series of daily measurements from several meteorological stations of Meteo France were
9 used: minimum and maximum temperature, rainfall, radiation (or its estimate from sunshine
10 hours for older data) and standard evapotranspiration from the Penman equation. For the
11 geographical sectors analyzed the weather stations used were: Abbeville (80), Bourges (18),
12 Dijon (21), Rennes (35), Nîmes (30) and Toulouse (31).

14 **1.2 Models and statistical methods**

15 **1.2.1 Choice of models and statistical fitting**

16
17 We chose to fit the time trends by linear regressions or pairs of straight lines – one rising
18 followed by a plateau (hereafter referred to as rising-plateau statistical model), or two
19 consecutive rising straight lines. Fisher's statistical tests for the significance of this trend
20 compared with the usual single linear regression were made and the following values of
21 probability (P) were used: very significant $P < 0.01$, significant $P < 0.05$ not significant $P > 0.05$.
22 This type of fit has the advantage of providing an estimate of the year of inflexion, or
23 transition. The same values of probabilities were used to test the significance of the
24 difference in the average of climatic indicators between two periods, using a non-parametric
25 Mann-Whitney test (Hothorn et al., 2008).

1.2.2 Treatment of the genetic data

In order to identify the yield gains resulting from genetic selection from the numerous trials available, it was imperative to remove the « noise » due to the yearly various climatic conditions. The methodology used was to choose a reference year and then to correct the yields step by step, based on the values of the lines present in 2 consecutive years in the network:

Let y_j^{i+1} the mean yield of genotype j on year $i+1$, yc_j^{i+1} the equivalent yield value corrected from the “year effect” and $n_{i,i+1}$ the number of lines common to years i and $i+1$. If i is considered as the reference year, the corrected values for all the lines of year $i+1$ are given by eq. 1.

$$\text{eq. 1: } yc_j^{i+1} = y_j^{i+1} + d_{i,i+1}$$

where $d_{i,i+1} = \frac{\sum_{j=1}^{n_{i,i+1}} (y_j^i - y_j^{i+1})}{n_{i,i+1}}$ is the initial “year effect” calculated relatively to the reference year i

Then, for year $i+2$, the corrected values, yc_j^{i+2} are given by eq. 2.

$$\text{eq. 2: } yc_j^{i+2} = y_j^{i+2} + dc_{i+1,i+2}$$

where $dc_{i+1,i+2} = \frac{\sum_{j=1}^{n_{i+1,i+2}} (yc_j^{i+1} - y_j^{i+2})}{n_{i+1,i+2}}$ is the “year effect” calculated relatively to the year $i+1$,

using the previously calculated “year effect” corrected yield value,

1 and so on for all the years posterior to i , and identically for all the years anterior to i .

2
3 At the end of this correction procedure, the mean yield of all the genotypes are related to the
4 reference year i , which in fact removes all the "year effects". The possible bias due to the
5 accumulation of correction errors can be considered as moderate if the number of lines
6 common to two consecutive years is high. This is the case for the INRA and CTPS sets of
7 trials as the best lines are included for 2 or 3 years and therefore 25-50% of the genotypes
8 are common to two consecutive years, insuring a good precision for the estimation of the
9 "year effect" each year.

10
11
12 A second treatment was applied to the dataset by keeping, each year, only the 20 best
13 genotypes, assuming that breeders generally prefer the highest-yielding lines. This choice
14 excludes several high-protein but lower-yielding varieties, which until now have only
15 represented a small proportion of the French cereal crop. It is these corrected and pruned
16 data which, by simple linear regression, have enabled us to estimate the genetic progress
17 due to selection.

18 19 **1.2.3 Crop modelling for climatic diagnosis**

20
21 We used two different crop models, as tools for revealing climate effects that give two
22 different points of view on the wheat agrosystem. By differences in the algorithm and factors
23 taken into account, those two models stand for two different technical options in terms of
24 inputs, which has been proved to act on the productivity-climate relationships (Reidsma et
25 al., 2009).

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1 They both rely on the same principles, allowing the estimation of the influence of climate on
2 crop yields in an integrated way by keeping the soil characteristics and farming practices
3 (variety, sowing dates, and fertilization) constant throughout the years and locations. They
4 are mathematical algorithms in which the weather, operating on a daily time step, acts as a
5 driving force (temperature, radiation) and as a stress generator (moisture deficit, extreme
6 temperatures). These models however do not take account of biotic constraints, such as
7 diseases, pests and weeds. Several families of crop models exist and the two models used
8 in this analysis belong to two different families, one of which is based on the elaboration of
9 yield components (PANORAMIX), and the other on the carbon balance and growth of the
10 plant (STICS). The principle on which PANORAMIX relies are described in Gate (1995) but
11 also in Meynard (1997) or Chatelin et al. (2005). It links the yield components sequentially in
12 pairs: number of stems per m² (input), number of ears per m², number of grains per m² and
13 single grain weight. These relationships are influenced by climatic variables or the soil water
14 balance averaged over critical phases of elaboration of each of the yield components. They
15 are updated every year from the results of the ARVALIS trial network established throughout
16 France and some of them are genotype-dependent. STICS (Brisson et al., 1998; 2003;
17 2009), like many crop models whose principles are described by Brisson et al. (2006), is
18 based on the carbon balance: interception of solar radiation by the foliage enabling the
19 atmospheric carbon dioxide, transformed into biomass of which some part is allocated to the
20 grain to form the yield according to relationships which are also genotype-dependent.

21
22 The differences between the PANORAMIX and the STICS models which can significantly
23 affect the results of this climate study are basically twofold. First PANORAMIX does not
24 include a nitrogen module, i.e. the crop is supposed to not suffer from nitrogen shortage,
25 while STICS simulates the complete soil nitrogen balance and the effect of nitrogen
26 fertilization, i.e. the dynamics of physicochemical processes in the soil and plant nitrogen
27 uptake which depend on climate on the whole annual basis. Second the STICS model
28 operates continuously so that the effects of resilience in the soil can be reproduced while

1 PANORAMIX assumes the soil to be at the permanent wilting point when the wheat is
2 harvested. As a consequence, the harmful effects of water stress will be maximized by
3 PANORAMIX in cases where the winter and spring rainfall is insufficient and does not allow
4 full recharge of the soil water profile. To sum up for PANORAMIX model, main climate
5 stresses are through soil water deficit and high temperature damages, while for the STICS
6 model there is an additional climate interaction through nitrogen (soil mineralization and
7 uptake) which can be positive or negative.

8
9 The simulation protocols of the two models are similar as regards the genotype (Bread
10 Wheat, cv Soissons), sowing date (10 October), soil water holding capacity (120 mm) and
11 weather (cf 1.1.3). Soissons, a mid early maturity type variety has been the most cultivated in
12 France for the last 20 years and thus was chosen as the reference throughout this climate
13 study. As far as nitrogen is concerned (for the simulations with STICS) the soil is assumed to
14 have an organic nitrogen content of 0.14% and the nitrogen fertilization of 200 kg N ha⁻¹
15 provided in three applications is sufficient but not excessive and does not necessarily ensure
16 that the crop is protected from nitrogen stress. Moreover the straw is recycled to the soil and
17 contributes to maintain soil fertility. Hence the two models do not simulate exactly the same
18 crops: PANORAMIX reproduces rather an intensive wheat crop whereas STICS simulates
19 one with limited inputs and a more conservative way to manage the crop.

20 2. Results

21 2.1 Yield evolution

22
23 The yield trend for bread wheat in France is shown in Figure 1, together with its two
24 calculation elements, production and area. One notices a stagnation in yields from the middle
25 of the 90s which is reflected in the production with a slight delay. This delay is explained by
26 an increase in the areas sown with wheat between 1995 and 1998, which had been stable

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1 since the beginning of the century. The stagnation of yields is very significant (P value of
2 Fisher's test is 0.00082) and the year of inflexion is estimated at 1996. Moreover, if one
3 excludes the year 1956 when a mass of cold air from Siberia caused a frost over the whole
4 French wheat crop, the year-to-year variability of production seems to have increased since
5 the start of the 21st century. Before 1996 the annual rate of increase of French yields was
6 $0.123 \text{ t ha}^{-1}\text{yr}^{-1}$.

7
8 This trend is also clear on a departmental scale (Figure 2) with an estimate for the year of
9 inflexion between 1991 and 1998. The departments selected are representative of the
10 general behavior since over the 52 cereal-growing departments there are 31% and 36%
11 which show a significant stagnation (at the 1% and 5% thresholds respectively). It should be
12 noted that it is the southern regions, with low yields, for which this inflexion of yields is most
13 often judged to be non-significant. We should point out an inconsistency due to the varying
14 sources of our data: in the western sector, the department in which the weather station we
15 used for the further climatic analysis (because of its long series of records) is situated, (cf
16 1.1.3) is the only one in the geographical sector to show insignificant yield stagnation.

17
18 The same trend was found in other European countries (Table 2

Country	Year of stagnation
Denmark	1995 (**)
France	1996 (**)
Germany	1999
Italy	1994
Netherlands	1993 (**)
Spain	1989
Switzerland	1990 (**)
United Kingdom	1996 (**)

19) with inflexion years between 1993 and 1996. Apart from the particular case of Germany, the
20 southern countries with low yields (Spain and Italy in which durum wheat, less productive
21 than bread wheat, is grown predominantly) are also those which show a non-significant
22 stagnation because of a concomitant increase in the year-to year variability.
23

1

2

2.2 Genetic causes

3

4 The variety trials presented in this study are the basis of certification of new varieties offered
5 to farmers (they are pre-registration or registration trials). The delay between the official
6 release of a new variety and its peak agricultural use is in the order of 6-7 years and has not
7 changed since 1989, as is shown by the statistics published by the National Interprofessional
8 Seed Group (GNIS, 2009). In other words the « lifespan » of varieties and their renewal rate
9 has not changed significantly. Hence the variety trials are a good reflection of the potential
10 for varietal improvement in French cereal growing.

11

12 Figure 3 shows the regressions of yield, adjusted for the « year » effect, as a function of time
13 for the three sets of variety trials. There is a very good fit to the data ($R^2 > 0.95$),
14 demonstrating that there is no inflexion in the linear trend over the study period, and so
15 genetic progress can be considered as continuous. It is estimated at 0.094, 0.115 and 0.128
16 $t\ ha^{-1}yr^{-1}$ for the $INRA_T$, $CTPS_T$ and $INRA_{NT}$ datasets respectively. The fact that genetic
17 progress is more rapid in the absence of fungicide treatment shows that the improvement in
18 yield potential is not made at the expense of resistance (or tolerance) to the fungal diseases
19 of wheat.

20

21 2.3 Agronomic causes

22

23 2.3.1 Nitrogen

24

1 The nitrogen status of crops can be altered in two ways: a reduction in the supply of fertilizer
2 with no change in crop requirement, or conversely an increase in crop requirements with no
3 change in the supply.

4 Figure 4, derived partly from survey results, illustrates the first point, i.e. the evolution of
5 fertilizer practices: an increase in the total amounts from 1996 to 2000, followed by a fall of
6 about 20 kg N ha⁻¹ between 2000 and 2007, whereas the number of applications seems to
7 have stabilized at around 3. As far as the second point is concerned, as demonstrated by
8 Lemaire and Gastal (1997) for many species (for wheat see Justes et al, 1994), the nitrogen
9 content needed for maximum yield depends on the aerial biomass. Now, as explained by
10 Peltonen-Sainio and Peltonen (1994) or Brancourt-Hulmel et al. (2003) genetic progress was
11 associated with an increase in harvest index (about 0.2% per year in France according to
12 Brancourt-Hulmel et al., 2003) and not in total aerial biomass. Consequently the only way
13 nitrogen requirements could have increased is through an increase in grain protein content,
14 while maintaining a high yield level; which is inconsistent with the well-known inverse
15 relationship between yield and grain protein content (Oury and Godin, 2007). It seems thus
16 reasonable to assume that nitrogen requirements have not increased.

18 2.3.2 Protection against diseases

19
20 Changes in the indicator of frequency of fungicidal treatments (protection against *Fusarium*
21 foot rot, *Septoria* leaf spot, powdery mildew and rust etc.), shown for three important cereal-
22 growing sectors in

23 Figure 5, do not show any significant trend. Several aspects of the wheat growing situation
24 should be mentioned to understand the fluctuations shown in the graphic. The dip in the
25 years 2002-2004 corresponds to a fall in wheat prices and the use of very effective new
26 chemicals (strobilurins) which can be applied at very low concentrations of active ingredient.
27 2003 was a year in which very little fungicide was used because of the combination of high

1 temperatures and drought. After 2003 resistance to strobilurins appeared, resulting in a
2 gradual return to less effective products, applied at higher concentrations. The highest peaks
3 followed a high inoculum pressure and a high wheat price which led to « insurance »
4 treatments (e.g. 2007, not shown in the graph).

5
6 Furthermore,

7 Figure 6 shows no relationship between falls in yield and severe damage on a national scale:
8 only the fall of 2007 seems to be attributable to severe damage in certain regions. On the
9 contrary, in 2008 an increase in damage was accompanied by an increase in yields, and the
10 low disease levels of 2003 and 2006 coincided with low yields. None of these data show any
11 clear relation between low yields and diseases.

12 2.3.3 Effect of the preceding crop

13
14 At the rotation level, a significant trend was found after 1999 in crops preceding wheat (
15
16 Figure 7) with an increase in oilseed rape from 20 to 30%. This increase was at the expense
17 of peas until 2003, and then more recently of maize. However the appearance of faba beans
18 in 2001 allowed a proportion of legumes in the rotations of about 15% to be maintained.
19 Hence about 10% of leguminous crops were replaced by rape, which depressed the yields of
20 the following wheat crop as shown in

21
22 Figure 7 b. In fact wheat after rape is significantly lower-yielding than wheat after legumes,
23 the difference tending to fall, from about 1 t ha⁻¹ in 2000 to about 0.8 t ha⁻¹ after 2000 (if one
24 ignores the exceptional year, 2003). A rapid calculation for the entire French crop for this
25 replacement gives a reduction in yield of 0.42 t ha⁻¹ for the period 1995-2006. Although this
26 decline is not steady, the annual mean can be used for comparison with other causes
27 mentioned: it is 0.035 t ha⁻¹ yr⁻¹.

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2.3.4 Soil organic matter

Soil degradation in intensive arable cropping is a cause sometimes suggested (Nicolas, 2005). The data available at a national scale (Figure 8) show a rather contrasted situation in terms of soil organic matter evolution. For example while in the East sector the soil organic matter is rather decreasing or stable, it is rather increasing in the Parisian Basin. It is thus difficult to conclude to a general soil degradation caused by intensification, which could be responsible for yield stagnation.

2.3.5 Comparison between farmers yield and agronomic trials

One way of assessing the global impact of crop technical management on yields is to compare farmers' yields with the results of agronomic trials at experimental stations where agricultural practices are optimal and soils are good. For the 3 geographical sectors shown (Figure 9) we see that the trends from the two data sources run parallel, showing that the causes of the increases and decreases of yield are the same whether the growing conditions are optimal (as for the agronomic trials) or not. In the North and Centre sectors we see essentially a constant difference between the two curves. In the Southeast sector not only the difference is much greater but also the regional yields are less variable because of the much greater proportion of poor soils than in the other two regions. The difference between the two curves can be used to measure the trend of agronomic improvement, or how growing conditions (practices and soil) are able to fill the gap between actual yield and that which is genetically possible. In order to confirm that experimental trials are close to optimal conditions, the increasing yield trend before 1996 was calculated for the two longest series: it is of 0.10 and 0.14 t ha⁻¹ year⁻¹ for respectively North and South-East, i.e. orders of

1 magnitudes comparable to the genetic progress or even higher (supporting the idea of an
2 additional agronomic improvement). Consequently, the data presented do not show any
3 deterioration in the agronomic improvement.
4

5 **2.4 Climatic causes**

6
7 The results obtained from crop modeling, either PANORAMIX (Figure 10) or STICS (Figure
8 11), which assumed similar techniques and soils for all the sites, can not be likened to real
9 yields: they are « climatic yields ». There is no doubt that, in a first approach, we rather
10 observe no significant results due to the important year-to-year variation proper to climate.
11 Linear relationships fit the data better than bilinear ones, but they are not significant
12 (coefficients of determination always below 0.04). The increase in year-to-year variability
13 towards the end of the period is visible in the STICS results (Figure 11) and tends to blur a
14 possible climatic effect for the last decade. In this statistically very difficult situation, we did
15 however test the bilinear model. We noticed that, in a quite autonomous way, it revealed
16 inflexion years which agreed with the yield observations (in particular there was agreement
17 for the sites in the south of France) and slopes for the post-inflexion period which were
18 always less steep than those before the inflexion. From these results we deduce that there is
19 indeed a worsening climatic effect, masked by the year-to-year variation which we will
20 attempt to estimate.
21

22 The factor responsible for PANORAMIX yield decrease, when this decrease is significant is
23 not always the same. For Bourges(18) and Dijon(21) it is the number of physiological heat
24 stress during grain filling (number of days on which the maximum temperature exceeds
25 25°C) with increases between the two periods (before and after the inflexion year 1993) of
26 respectively 11.1 to 13.4 days (highly significant as a result from the Mann-Whitney test) and
27 12.8 to 15.5 days (significant). For Nîmes, it is the drought suffered by the crop during the

1 stem elongation and grain-filling stages, calculated as the difference between the cumulative
2 rainfall and the potential evapotranspiration: it increases highly significantly from 37 to 67 mm
3 between the two periods (i.e. before and after 1988).
4

5 As expected, the yields calculated with STICS are lower than those calculated with
6 PANORAMIX; the inflexion point, when it exists, is also more pronounced with the latter. An
7 explanation is provided by

8 Figure 12 which represents the nitrogen accumulation in the plant simulated by STICS: it
9 increases noticeably after 1990 under the influence of rising temperature which stimulates
10 the mineralization of organic matter, leading to better nitrogen nutrition of the crop (the N
11 stress indexes also show it). In other words in STICS the harmful effects of the climate are
12 partly balanced by this beneficial effect, allowed to a large extent by the straw recycling. It is
13 also interesting to note that during the period preceding the transition, with a supposedly
14 stationary climate, the yield often shows a slightly rising trend, in particular with the STICS
15 model (e.g. the cereal regions of northern France show a trend of $0.02 \text{ t ha}^{-1} \text{ yr}^{-1}$).
16

17 In order to estimate the magnitude of the climatic penalty on yields, we have calculated the
18 change in slope after the transition by subtraction of the regression coefficient after the
19 transition from that before it (Table 3). The change in slope differs for the two models;
20 PANORAMIX gives higher values than STICS; they also vary more from site to site. On the
21 other hand, for both models the median transition year for the 6 sites is 1990.
22
23

24 **3. Discussion**

26 **3.1 Yield evolution**

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The observation of yield stagnation in wheat in France is not an exception, and an identical trend is also found to be significant in all the northern European countries except Germany, confirming the Finnish (Peltonen-Sainio et al., 2009a) and Swiss (Finger, 2008) results. As to Germany, the political and economic changes due to reunification in 1990 caused acceleration in the yield trend in the east of the country (Koester and Brooks, 1997), explaining the delay and the lack of significance found for the stagnation. On a departmental scale, the French results agree with the national scale, showing that the national results are not the result of a compensatory effect between departments.

Although the stagnation is judged non-significant (at the 5% threshold) in the southern regions with low yields (Spain, Italy and the southeast and southwest sectors of France), this is because of the increase in year-to-year variability and not because the increasing trend is continuing. Furthermore the rising-plateau statistical model used represents an extreme situation: it is possible that although it does not actually level out, the reduction in the slope could be significant.

The period over which the stagnation begins extends from 1990 to 1998. However the most frequent year is 1996, in agreement with the results of Peltonen-Sainio et al. (2009). By using quadratic models Kumar Boken (2000) had already shown a tendency for the yield increase to level out, without however being able to define precisely the inflexion year; this is possible with the rising-plateau model used in this study. But whichever statistical technique is used, this finding casts doubt on studies of economic prospects based on steadily increasing yield levels such as the A1 or A2 SRES scenarios and rather support B2 type SRES scenario (Ewert et al., 2005). The question is to know whether the B2 determinants for yield level off could provide relevant explanations for the current trend, i.e. low technology level and an

1 important yield gap between potential and actual yields due to low input agriculture
2 increasing.

3

4 **3.2 Genetic cause**

5

6 As in Finland (Peltonen-Sainio et al., 2009a), there is thus no perceptible limitation to genetic
7 progress in France. The idea advanced by Calderini and Slafer (1998) for wheat and by
8 Cassman (1999) for rice, according to which yields are close to a genetic plateau, is not
9 supported. Genetic progress in wheat is made in two directions. The increase in yield
10 potential (in the absence of constraints) in the order of $0.104 \text{ t ha}^{-1}\text{yr}^{-1}$ (from the average of
11 the results of our two sets of trials) is largely due to the increase in the harvest index. It is
12 comparable to that estimated in Mexico: $0.103 \text{ t ha}^{-1}\text{yr}^{-1}$ (Bell et al., 1995) and explains most
13 of the yield increases on the national scale ($0.123 \text{ t ha}^{-1}\text{yr}^{-1}$). The larger increase in the
14 untreated wheat yield shows that there is a parallel improvement in resistance to fungal
15 diseases, making the new varieties better prepared for more extensive cultural practices or
16 limited inputs. It is possible that this increased resistance (genetic progress under constraint)
17 contributes, together with the improvement in cultural practices (in particular the increase in
18 nitrogen fertilization: cf 2.3.1) to the explanation of the positive difference between the
19 increase in national yields (before 1996) and the genetic progress without constraints. This
20 tends to indicate that the crop protection is on average less good in farming practice than in
21 the variety trials, for which the standard of crop protection is often optimal.

22

23 We should point out however that the method of calculation, favoring the high yields by
24 selecting the 20 best varieties, may result in a slight overestimate compared with the real
25 value resulting from farmers' choices. In fact we find in certain regions increasing use of
26 high-protein bread wheats whose potential yields are not always the highest.

3.3 Agronomic causes related to economic aspects

Agronomic diagnosis is very important as it is at this level that socio-economic pressure is exerted: this happened during the economic growth of the fifties in Europe (Calderini and Slafer, 1998), very well simulated by Gervois et al. (2009), and it is the main argument put forward by Peltonen-Sainio et al. (2009a) and Finger (2008, 2010) to explain the stagnation of yields in Finland, Switzerland, Germany and France. The list of technical causes which we have produced shows that farmers have been able to modify their practices, probably influenced by various inducements, such as CAP initiatives and wheat prices. These changes, however, only began in 1999.

In particular we have recorded a tendency for nitrogen fertilizer rates and the use of legumes (as preceding crops to wheat) to decline. The reduction in nitrogen fertilizer rates of about 20 kg N ha⁻¹ (a figure also suggested by Peltonen-Sainio et al., 2009a although not directly comparable as it referred to spring wheat) has been accompanied by an increase in its efficiency by increasing the number of applications; this might also explain the reduction in wheat yield difference between the peas and rape seed as preceding crops. According to the available technical references (Laurent and Makowski, 2007), this reduction in fertilization would tend to depress yields of about 0.1 t ha⁻¹ (varying between 0 and 0.2 as a function of soil type), which would correspond to 0.015 t ha⁻¹ yr⁻¹ for the period concerned (2001-2007). However such a reduction assumes that all the farmers manage their fertilization optimally, whereas suboptimal nutritional conditions were often prevailing, suggesting that the fall of 20 kg N ha⁻¹ could have a lesser effect. But this effect cannot be ignored because at a more global scale, Reidsma et al. (2009), from economical data of the FADN¹, show a strong relationship between fertilizers and wheat yield.

¹ FADN : Farm Accountancy Data Network

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1 As far as diseases are concerned we have found no convincing factor. The role played by
2 strobilurins and the appearance of resistance to them largely explains the irregularities in the
3 indicator of frequency of treatments which cannot be related to a reduction in fungicide
4 protection. Furthermore the genetic trials have shown an improvement in disease resistance.
5 Finally, the absence of a relationship between damage and yield reduction tends to rule out
6 diseases as a major cause of yield decline. This result is corroborated by Reidsma et al.
7 (2009) analysis at the European level.

8
9 Our data do not allow us to suggest soil degradation as a possible cause of yield stagnation,
10 in the form of a general declining fertility at a national level. Other soil components as
11 physical degradation could be evoked, but no data are available at a national scale. Yet the
12 general movement of soil tillage simplification tends to improve soil physical structure.
13 Consequently we will not retain soil degradation as a possible cause of yield stagnation at a
14 national level.

15
16 The most plausible technical explanation for the stagnation of yields seems to be the
17 noticeable change in rotations, which favored growing rapeseed after 1999 and in particular
18 brought about a reduction in legumes of about 5-10%. It is the second of these two points
19 which would tend to depress yields.

20
21 Figure 7 b separates two groups of preceding crops: legumes on the one hand which boost
22 yield, and other crops (rape and wheat), which are rather unfavorable to yield. The reason is
23 well-known to agronomists. The nitrogen status of the soil at sowing and during the winter is
24 much better after a legume crop (Jensen, 2006) for two reasons: the soil mineral nitrogen not
25 uptaken by the legume is available to the wheat and the mineralization of the crop residues
26 liberates more nitrogen than that of other preceding crops. Conversely rape seed, like wheat,
27 is a great nitrogen consumer, so much so that it is used as a catch crop to trap nitrate
28 (Justes et al., 1999). Attempting to deal with these well-known agronomic problems by

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1 adjusting the fertilization of the wheat according to the preceding crop does not allow to
2 exactly counterbalancing the effects of the two types of preceding crop because the
3 dynamics of the availability of the N are different. For the mineralization of legume residues it
4 is slow, but with extra mineral fertilization it is immediate, making it more liable to leaching.
5 The fact that an improvement in the efficiency of fertilization by splitting the dose (from 2000)
6 noticeably reduces the difference between the two groups of preceding crops supports this
7 hypothesis. The calculation made for the entire French crop allows us to attribute an average
8 annual loss of $0.035 \text{ t ha}^{-1} \text{ yr}^{-1}$ to this effect.

9
10 More generally, the continuation of what we have called agronomic progress, attested by the
11 parallelism between the results of trials at experimental stations, carried out using optimum
12 techniques, and the regional statistics, does not show any pronounced tendency towards
13 technical changes or to migration of wheat onto different soils (which could result in a
14 divergence between the two curves), contrary to the suggestions of Peltonen-Sainio et al.
15 (2009a). Our results corroborate the economic findings of Butault (2006) which show, by the
16 analysis of the inputs used by farmers, that no lessening of farming intensity is perceptible in
17 France. Does this contradict the earlier estimates leading to a yield penalty that may reach
18 $0.05 \text{ t ha}^{-1} \text{ yr}^{-1}$ due to technical causes (fertilization + rotation)? One has to accept that in
19 **Erreur ! Source du renvoi introuvable.** this inflexion would correspond at the most to 5% of
20 the difference between the two curves and would be difficult to discern. On the other hand
21 these estimates are very approximate and are based on changes which began after the
22 turning point of 1996. Between 1996 and 2000, everything indicates that agronomic progress
23 continued (fertilization, plant protection, and rotations) and cannot therefore be the main
24 cause of the yield stagnation. Looking towards our neighbors to the north, whose
25 environmental policies are much stricter than in France, important changes in practices were
26 noted. For example in Denmark the frequency of fungicidal treatments fell by 50% in 10
27 years. We find however a yield trend similar to that in France, indicating that there must be
28 another cause which transcends national boundaries.

1

2

3.4 Climatic cause

3

4 Although the climate is recognized as being responsible for year-to year variability in yields, it
5 is never directly mentioned as a cause of yield stagnation for wheat or other cereals in
6 Europe, although it is in Asia for wheat (Kalra et al., 2008) and rice (Lahda et al., 2003).
7 However, in our results, the climate, by its trend over the last two decades, seems to be one
8 of the possible causes of stagnation of yields. The year-to year variability of the climate
9 masks this trend, which appears in the « climatic yields » more like a vague suggestion than
10 a clear trend: the signal/noise ratio is low. This no doubt explains why this trend was not
11 mentioned in the latest IPCC report (2007). Although we have detected changes in the trend,
12 there is also at times an increase in the variability. For the Nimes site this increase in
13 variability explains the one found on the raw yield data.

14

15 If we look at the trends, the climate-related yield losses calculated with the PANORAMIX
16 model can be high, about the same order of magnitude as the genetic progress (e.g. at
17 Dijon). With the STICS model the losses are smaller because of the beneficial effect of the
18 stimulation of soil organic nitrogen mineralization. We should note, however, that the
19 simulation protocol of STICS, with a high level of crop residue, exacerbates this effect
20 whereas PANORAMIX takes no account of it at all. As far as water relations are concerned,
21 the assumption made in PANORAMIX, whereby the soil is emptied of water at the end of
22 summer, tends to exaggerate the effects of drought, and also increases the difference in
23 behavior between the two models. We should bear in mind that the levels of inputs assumed
24 in PANORAMIX are greater than those of STICS (which is attested by the higher yields with
25 PANORAMIX) and the behavior of PANORAMIX reflects the fragility of intensive agriculture
26 when faced with unpredictable weather. An estimate of the mean climatic penalty is 0.021 t
27 ha⁻¹ yr⁻¹ (STICS) and 0.046 t ha⁻¹ yr⁻¹ (PANORAMIX). We should retain these two figures as

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1 lower and upper bounds for this penalty, with the high values corresponding mainly to crops
2 grown optimally.

3
4 Climate change, which amounts to a general warming, is accompanied, in France, by an
5 increase in the frequency of winter and spring droughts, i.e. during the period of stem
6 elongation of wheat. These changes have repercussions on the development and physiology
7 of crops as well as on their water and nitrogen nutrition. The acceleration of the biological
8 clock resulting from the increased temperature brings forward developmental stages and
9 slightly reduces the growing period between flowering and maturity. This shift is not enough
10 to protect the crop from the harmful effect of high temperatures during grain filling. Although
11 the underlying mechanisms of high temperature damage are still poorly understood, we know
12 empirically that maximum temperatures above 25°C significantly reduce individual grain
13 weight (Gate, 2007 ; Gooding et al., 2003). In our study, we find that it is not the southern
14 geographical sectors, where these phenomena are common, which are most affected, but
15 rather those in the north, which previously were unaffected by heat stress. In very different
16 climatic conditions from those of France, Kalra et al. (2008) show from real data that Indian
17 cereal yields (wheat and barley in particular) have fallen by 0.2 - 0.5 t ha⁻¹ per degree Celcius
18 increase in temperature. Applied crudely to the increase which has taken place in France
19 (about 0.05 °C per year since 1990), these figures lead to yield reductions of about 0.01 -
20 0.025 t ha⁻¹ yr⁻¹, roughly similar to ours, bearing in mind that that we are only concerned here
21 with temperature. Modeling shows that the use of early varieties and enhancing the sowing
22 date ought to limit these losses (Kalra et al., 2008 ; Gate, 2007) but this problem needs to be
23 studied experimentally to define these conditions.

24
25 Water factor, especially drought during stem elongation, which has often occurred in recent
26 years, also tends to reduce yield by reducing the number of grains (Sinclair and Jamieson,
27 2006). Several factors combine to aggravate the situation : a reduction in winter rainfall do
28 not enable the soil moisture profile to be fully recharged (1996, 1997, 2002, and 2005) or on

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1 the contrary excess winter rainfall restricting rooting (2001, 2003, 2007) or excess rain after
2 flowering (2007, 2008), increased evapotranspiration during ear emergence and a lack of
3 spring rain (1996, 1997), very low radiation at the time of fertilization of the flowers (2008),
4 and finally inadequate frost hardening of wheat associated with very severe cycles of frost
5 and thawing (2003)

6
7 The beneficial effect of higher temperatures on nitrogen mineralization is reported in several
8 studies on the impact of climate change (Dueri et al., 2006; Eckersten et al., 2000) which
9 lead to estimates of increases of 2-9 kg N ha⁻¹ yr⁻¹ depending on the soil type and the
10 cropping system. In our study, based on a relatively poor soil, we found an increase of about
11 1-2.5 kg N ha⁻¹ yr⁻¹ of nitrogen accumulation in the plant due to this phenomenon. This might
12 explain the time lag of several years between the beginning of the climate change effects
13 and the limitation of yields. However in the long term it is probable that this effect will become
14 blunted by the adaptation of the microorganisms to high temperatures (Sierra, personal
15 communication.) or by changes in the composition of crop residues (Dalias et al., 2001). As
16 far as the past period is concerned, it is not possible to consider this beneficial effect of
17 temperature increase on mineralization as a compensation for decrease in nitrogen
18 fertilization or decline of legumes in the rotations, because our estimations rely on a great
19 amount of recycled wheat crop residues, which is not the standard practice.

20
21 In certain regions the positive trends in « climatic yield » simulated by STICS before the
22 transition point tend to show that the combination of weather factors of the years 1960-1990
23 would have been favorable to agriculture and would have accompanied the yield increases of
24 crops grown under nitrogen-limiting conditions, as simulated by the STICS model. Hence the
25 climate, seemingly stationary if its components are viewed independently (temperature,
26 radiation, rainfall...), might not be if examined by multivariate calculations, here represent by
27 the « weather yield » computed by the crop model. Within the STICS model, the interactions
28 between crop growth and climate are both more numerous and more complex (direct and

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1 indirect, positive and negative: e.g. impacts of temperature and soil water status on
2 emergence and nitrogen availability, impacts of water logging and frost) than in the
3 PANORAMIX model (only water deficit and final thermal stresses), which could explain that
4 the positive trend is exhibited by STICS results preferentially. Accounting for Fig. 12, it is
5 legitimate to reject some cumulative artifact that could have occurred with STICS leading to
6 a nitrogen accumulation since the beginning of the simulation series that could have
7 artificially increased yield. Going further in this analysis would be out of the scope of the
8 present paper but it could be worthwhile to confirm and explore this slight positive trend in
9 the “climatic yield” of the 1960-1990 period.

10 Conclusions

11
12 The large amounts of data used, and the methods employed in this work, allow us to
13 estimate the relative importance of the factors affecting yield and to reveal the causes of their
14 stagnation since the middle of the 1990s. Although we have shown that genetic progress has
15 not declined (between 0.10 and 0.12 $\text{tha}^{-1}\text{year}^{-1}$), it has been partly counteracted by climate
16 change which in general is unfavorable to cereal yields (e.g. high temperatures during grain
17 filling, drought during stem elongation) (estimated between -0.02 and -0.05 $\text{t ha}^{-1} \text{yr}^{-1}$). This
18 depressive effect of climate seems to have been greatest in the regions of intensive cereal
19 growing, with high yield potentials. We cannot however, from the decade beginning in 2000,
20 rule out agronomic causes and in particular the decline in legumes in the cereal rotations,
21 replaced by oilseed rape and to a lesser extent the decrease in nitrogen fertilization that both
22 might have reach -0.05 $\text{t ha}^{-1} \text{yr}^{-1}$. Our results point out the sensitivity of high input agriculture
23 (at least for rainfed wheat), to climate, and at the mercy of simplification in crop rotations.
24 Such results do not completely agree with the hypothesis on which prospective SRES
25 scenarios studies are based (Ewert et al., 2009): the more intensive the agriculture, the
26 easier the genetic potential yield to reach. Yet our estimations let us think that the depressive

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1 effects of climate and practices modifications do not compensate for the beneficial effects of
2 genetical progress, which opens research issues quite important, particularly in terms of
3 methodology to approach explanation of productivity evolution at national scales.

4

5

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10

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Type of data	Nature of data	Source of data	period	Geographical sectors						National scale
				North	Center	East	South-East	West	South-west	
Statistical surveys	Production, area	AGRESTE ¹ FAO ²	1956 2007	x	x	x	x	x	x	x
	Practices	ONIGC ³ ARVALIS ⁴ AGRESTE	1994 2009	x	x	x				
Controlled trials	Damage		2001 2008	x	x	x	x	x	x	x
	Yield and optimal practices	ARVALIS		x 1981 2008		x 1996 2008	x 1982 2006			
	Yield of each variety	INRA ⁵ _{NT} INRA _T	1970 2008 1982 2008	x	x	x		x		x (Northern France)
		CTPS ⁶ _T	1994 2008							
Soil survey	Soil organic matter	INRA	1990 2004							x
Modelling	Weather yields	METEO FRANCE ⁷	1956 2007	x	x	x	x	x	x	
	Phenoclimatic indicators			x		x	x			

Table 1 : Summary of data used in the study (T and NT subscripts refer to breeding networks: see in the text).

¹AGRESTE : Statistical service of the French ministry of Agriculture

²FAO : Food and Agriculture Organization of the United Nations

³ONIGC : French National Office for Arable Crops

⁴ARVALIS : French technical institute for cereal crops

⁵INRA : French National Institute for Agronomic Research

⁶CTPS : French Technical Committee for Breeding

⁷METEO FRANCE : French meteorological service

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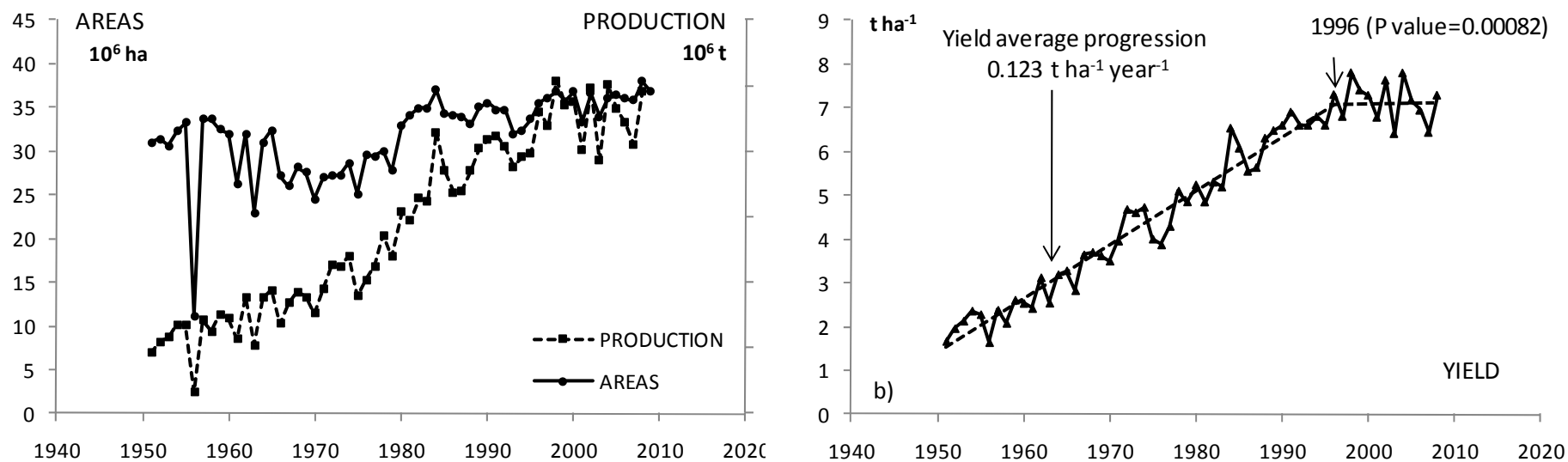


Figure 1: Annual evolution of bread wheat areas and production in France (a) and the subsequent yield (b). Optimization of the rising-plateau statistical model gives 1996 as the year of inflexion. The P-value results from the Fisher test comparing the rising-plateau model with the linear regression. Data source: AGRESTE

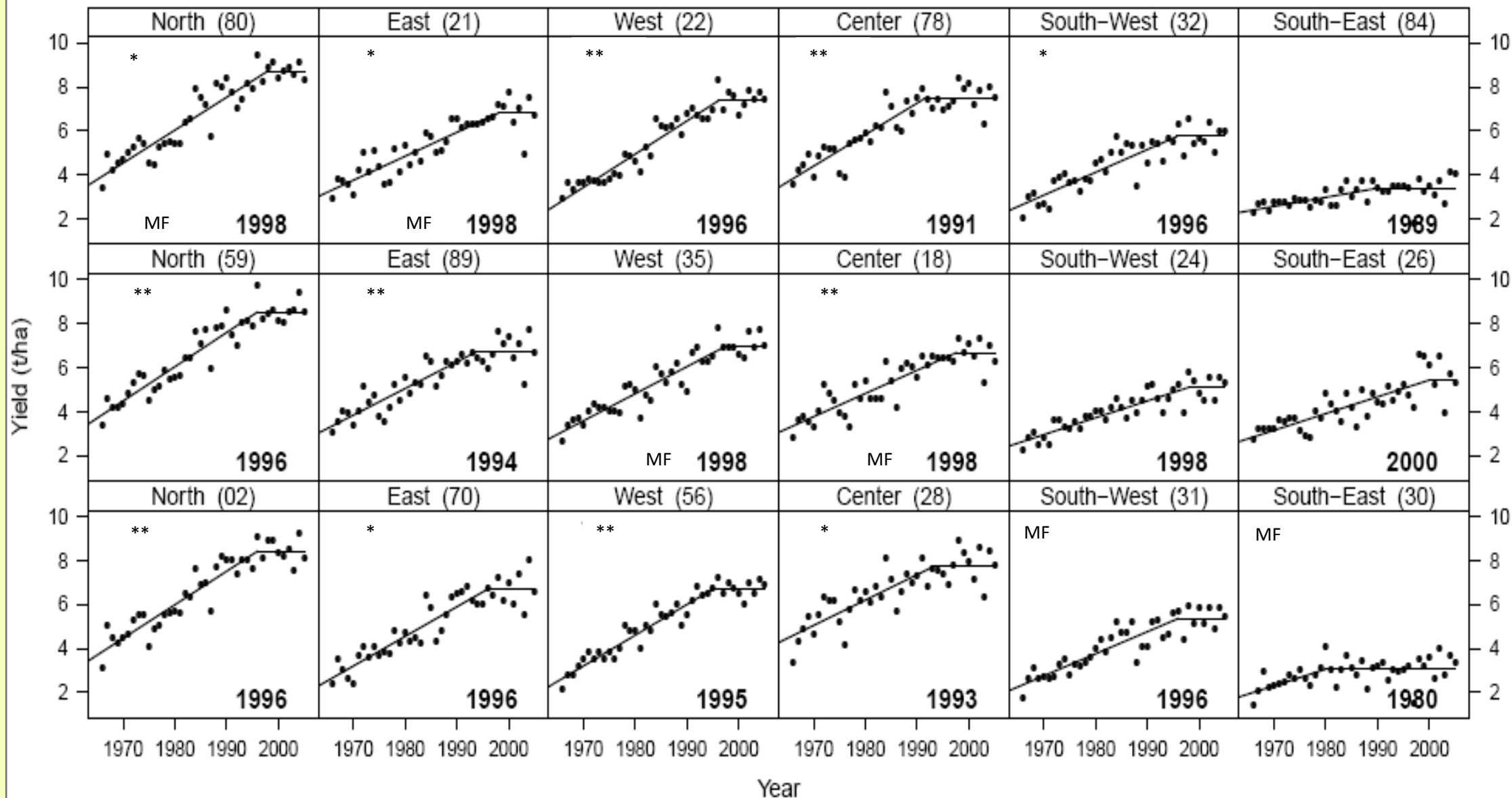


Figure 2 : Departmental yields distributed in the 6 geographical sectors (3 departments per sector) with the rising-plateau regression, the year of stagnation and the significance of this evolution compared to the single sloping straight line (** very significant $P < 0.01$, * significant $P < 0.05$, no star $P > 0.05$). “MF” indicates departments where meteorological stations used in the study are located. Source of data : AGRESTE

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Country	Year of stagnation
Denmark	1995 (**)
France	1996 (**)
Germany	1999
Italy	1994
Netherlands	1993 (**)
Spain	1989
Switzerland	1990 (**)
United Kingdom	1996 (**)

Table 2 : Results of the rising-plateau regression yield analysis throughout various European countries in terms of the year of stagnation and the significance of this evolution compared to the single sloping straight line (** very significant $P < 0.01$, no star $P > 0.05$) Source of data : FAO

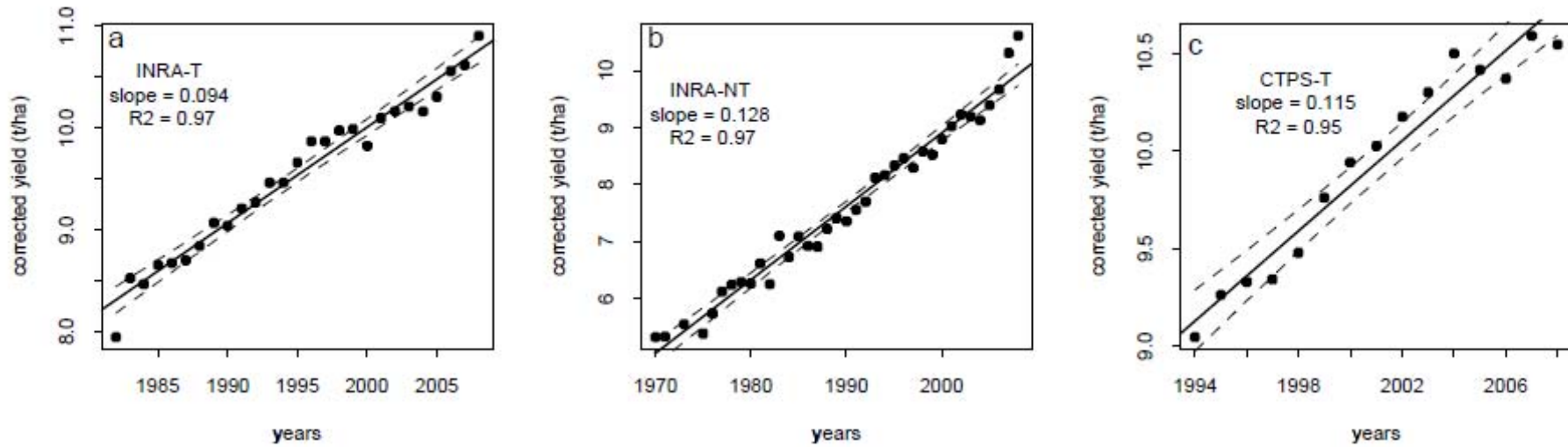


Figure 3 : Estimation of the genetic progress from yield evolution in the varietal trials of INRA with (a) and without (b) fungicides and of CTPS (c). Data are corrected for the year effect and averaged for the 20 best genotypes. Source INRA, CTPS

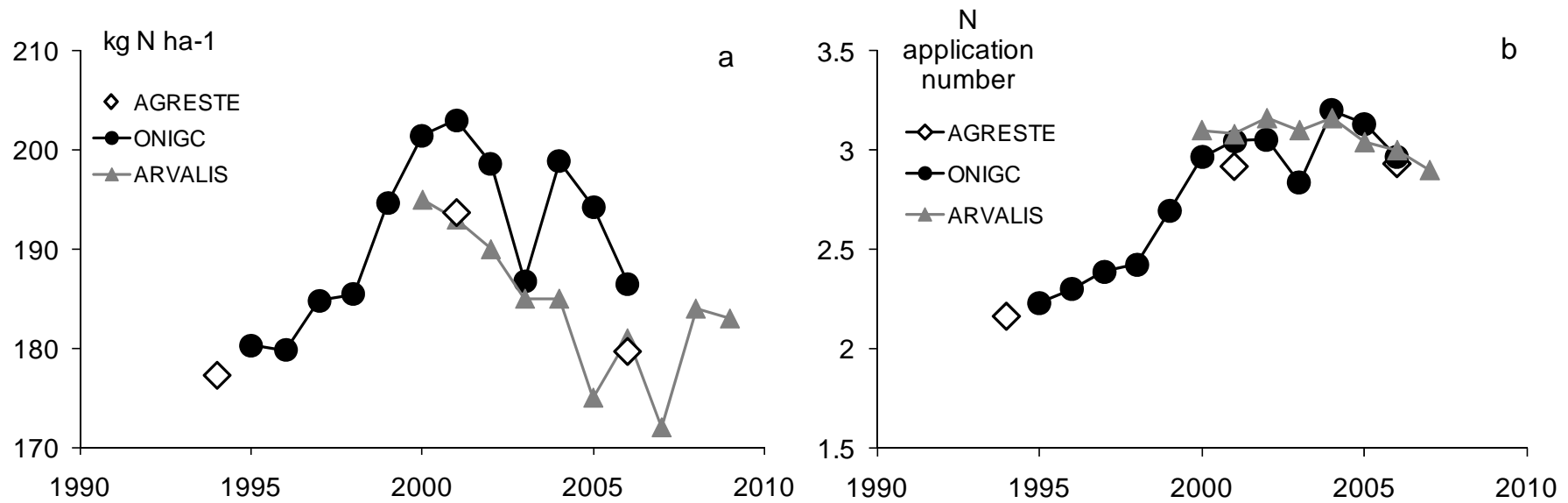


Figure 4 : Evolution of nitrogen fertilization according to 3 different sources (AGRESTE, ONIGC and ARVALIS) : a) total amounts ; b) number of applications.

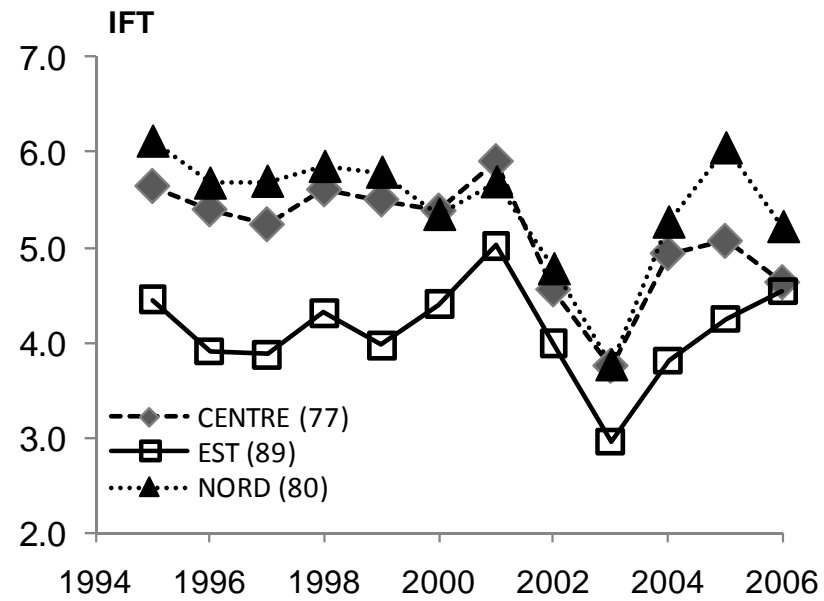


Figure 5 : Indicator of fungicides treatment frequency (IFT) in 3 sectors. Source : ONIGC

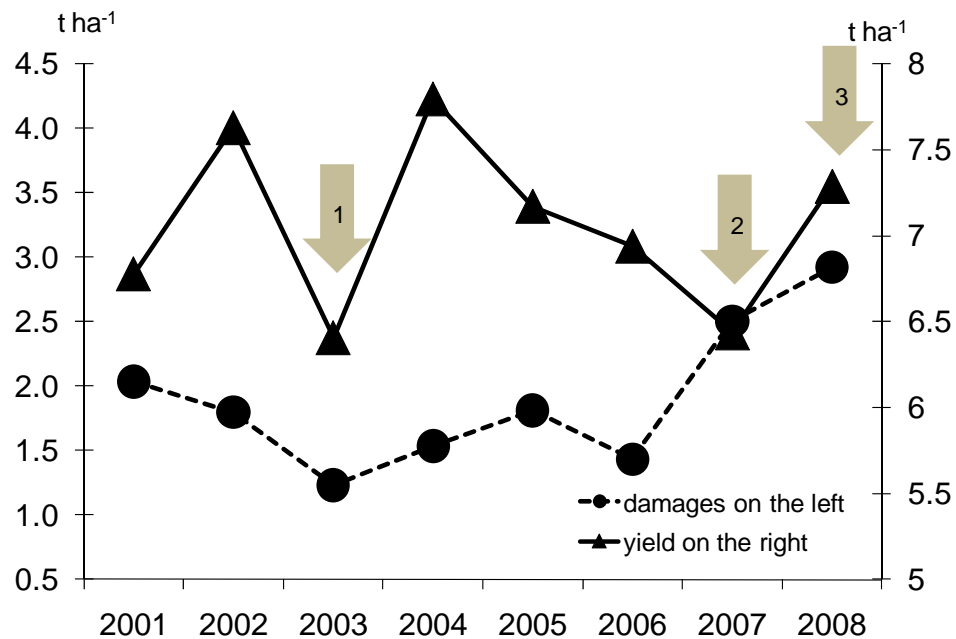


Figure 6 : Evolution of damage – yield. Identification of three cases: 1 with low damages and low yields, 2 with high damages and low yields and 3 with high damages and high yields. Source: AGRESTE, ARVALIS damage trials

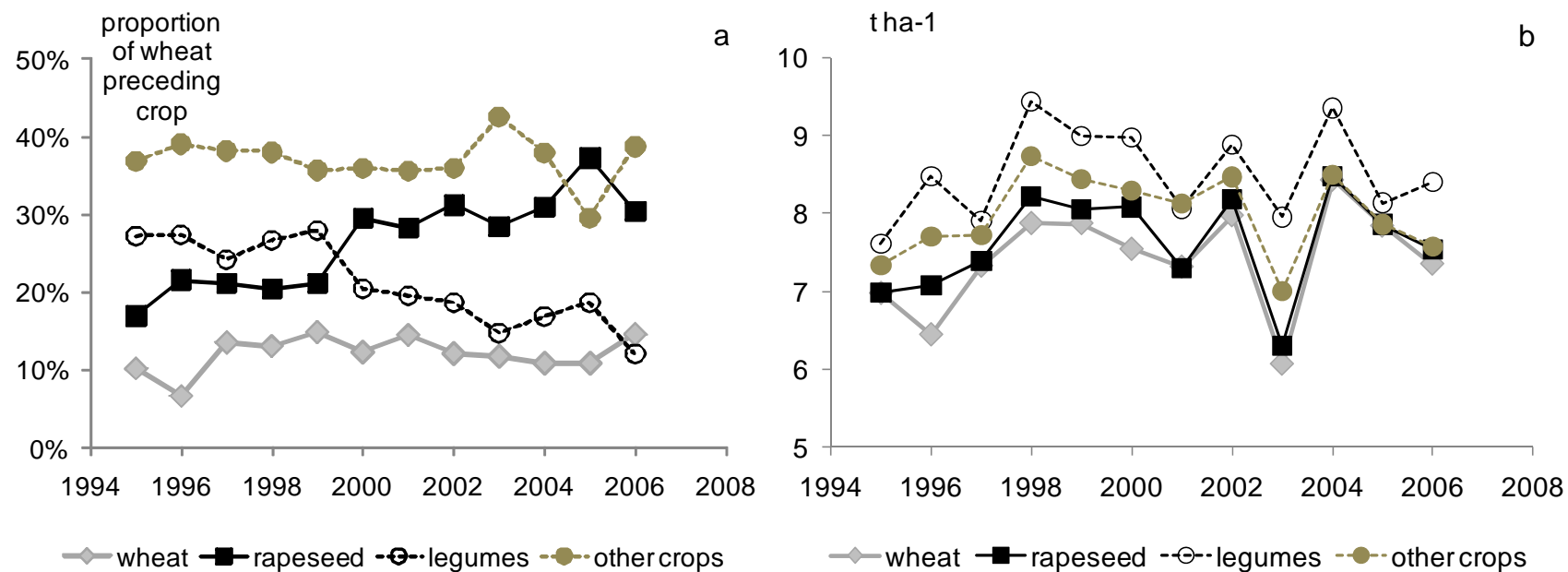


Figure 7 : Changes in preceding crops for wheat in surface proportion (a) and their effects on wheat yields (b). Source : AGRESTE

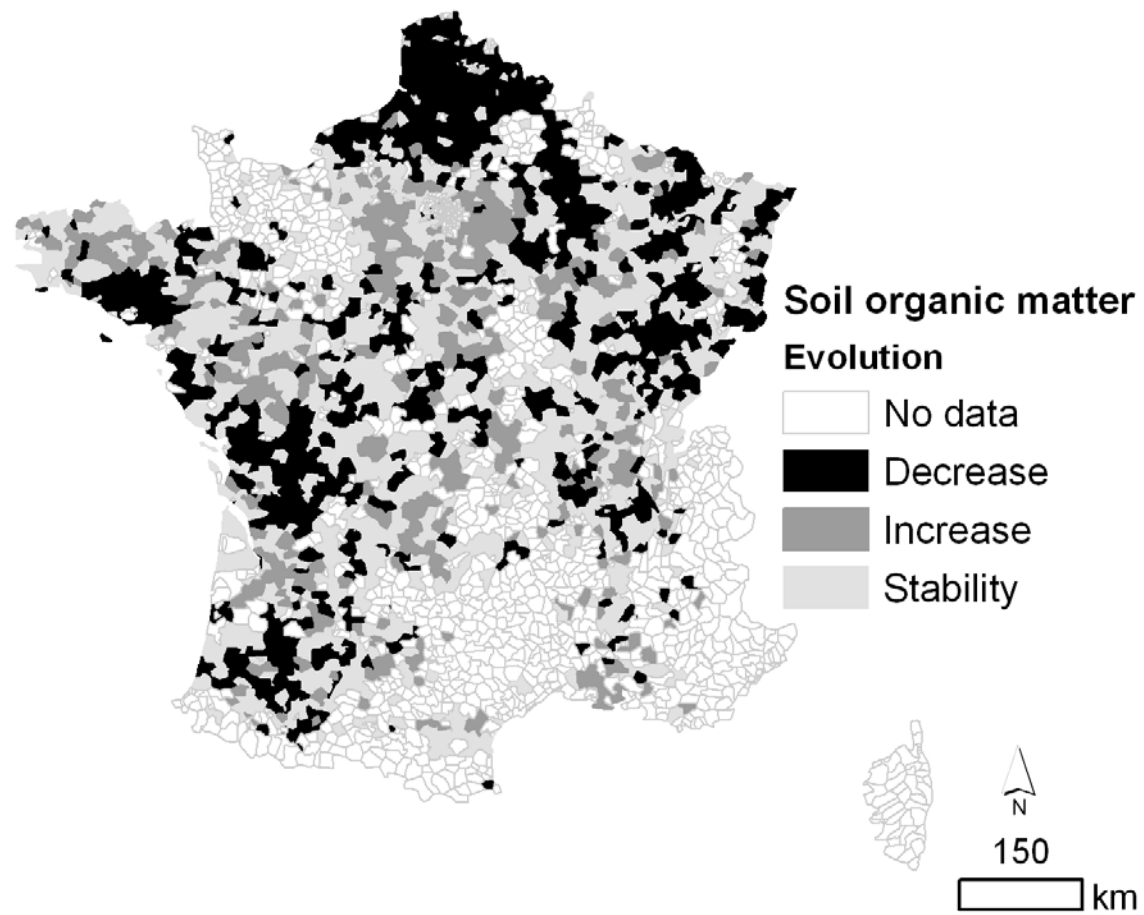


Figure 8 : Soil organic matter (organic C in g kg^{-1}) evolution between 1990-1994 and 2000-2004 periods. Source : INRA

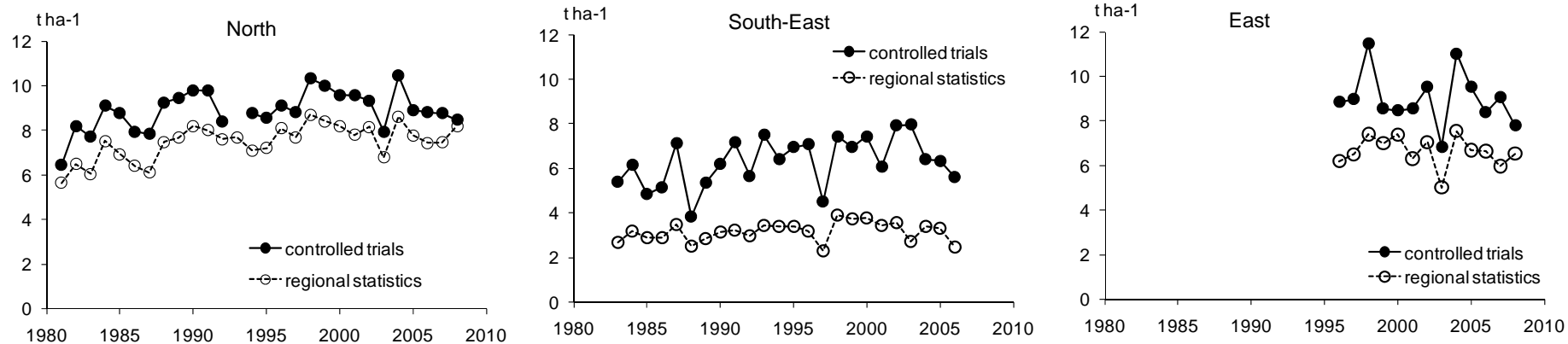


Figure 9 : Yield trends from regional statistics and agronomic trials Sources: AGRESTE, ARVALIS

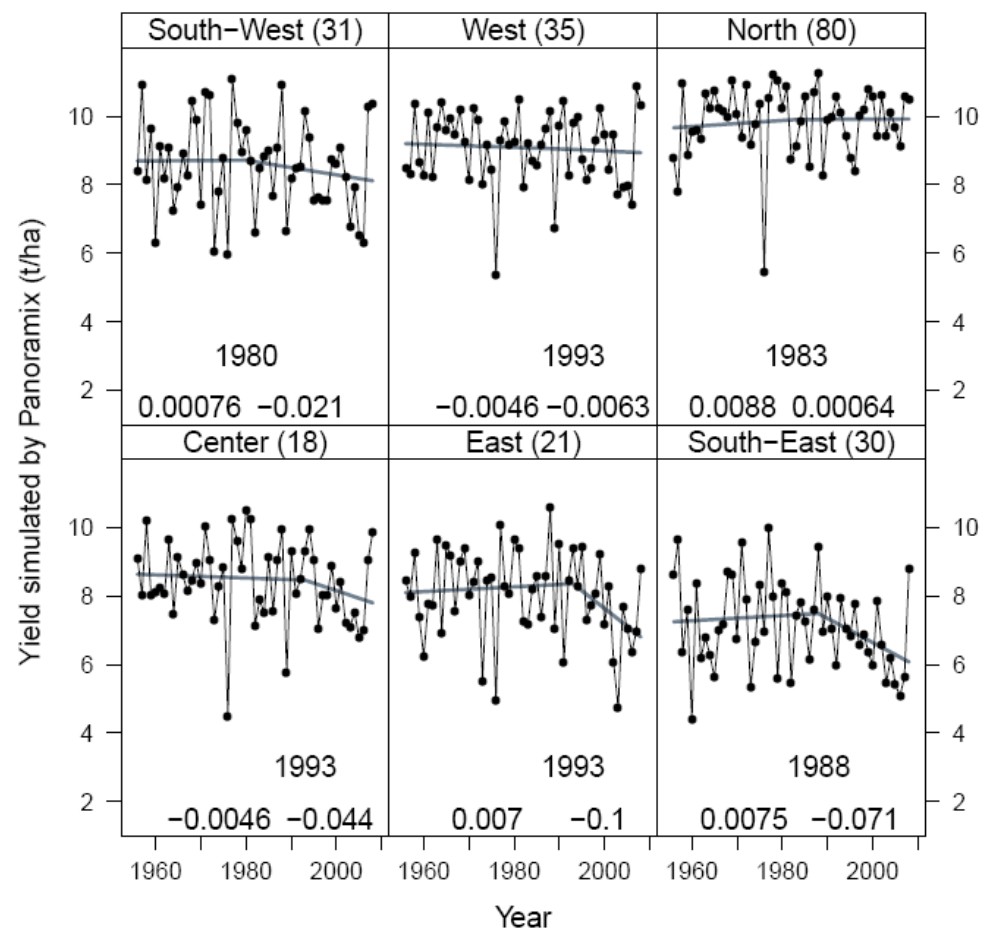


Figure 10 : Modeling of « weather yields » calculated with the PANORAMIX model for the 6 sites used. The straight lines correspond to the bilinear fits ; the transition year and the two regression coefficients are given below them. Sources: METEO-France

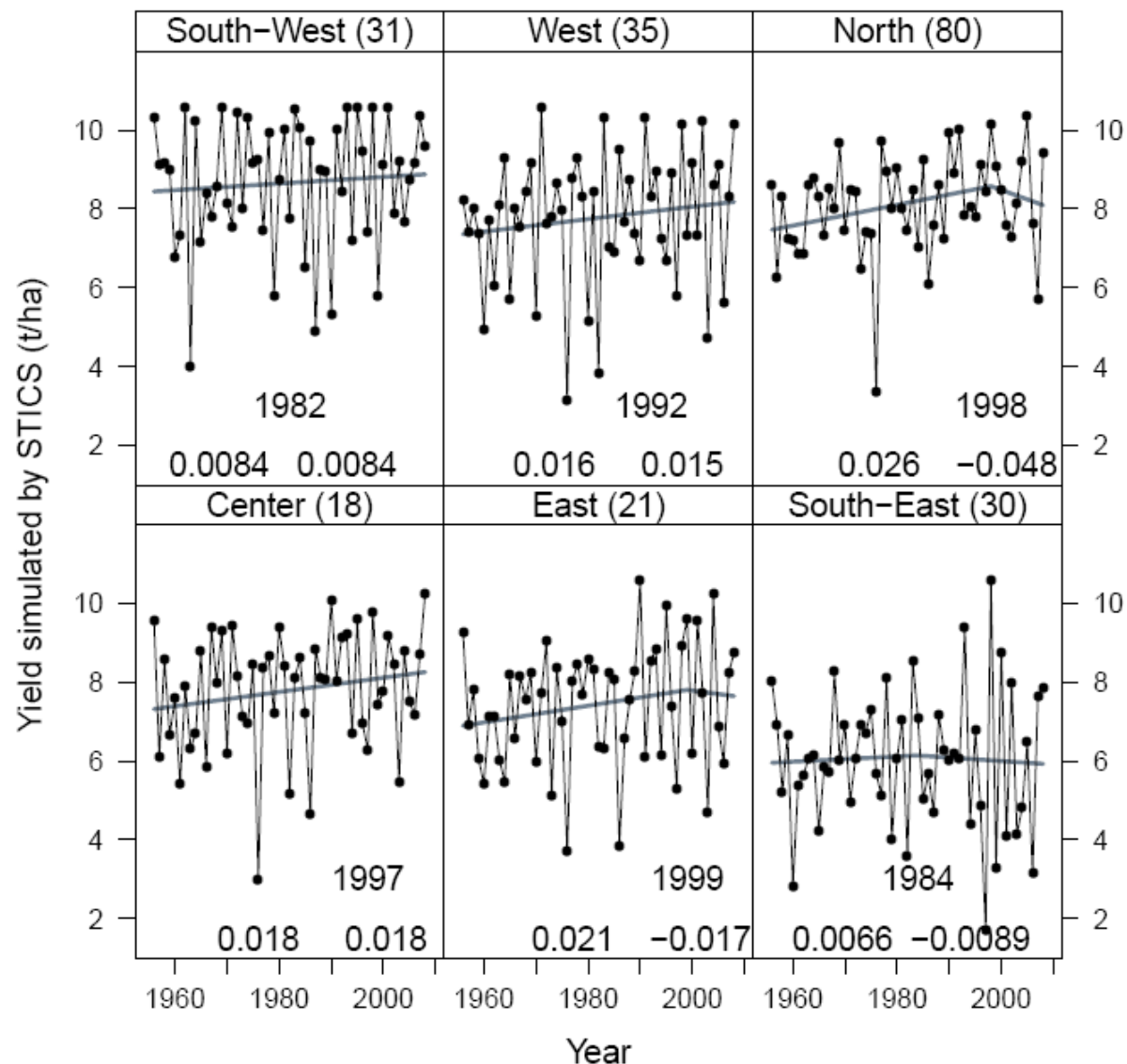


Figure 11 : Modeling of « weather yields » with the STICS model for the 6 sites studied. The straight lines correspond to the bilinear fits; the transition year and the two regression coefficients are given below them. Sources: METEO-France

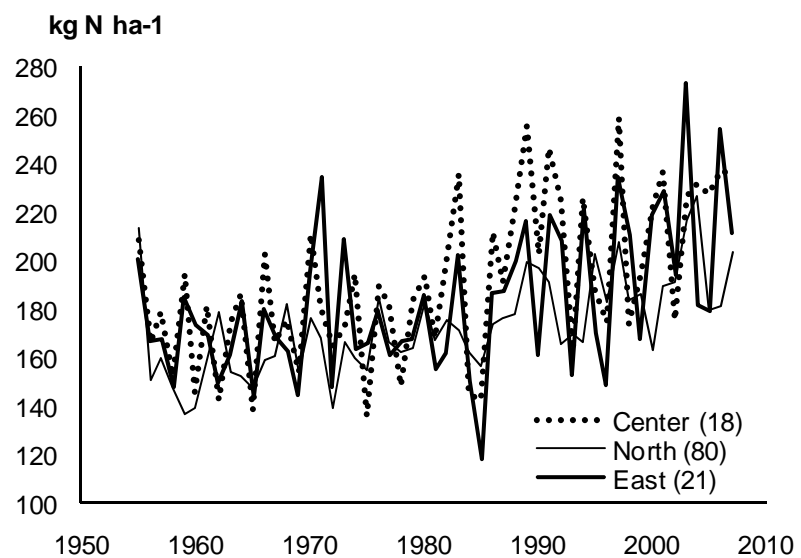


Figure 12 : Modeling of nitrogen accumulation in the plant at harvest simulated by STICS for three of the sites

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locations	Estimation of the climatic penalty of wheat yield ($t\ ha^{-1}\ yr^{-1}$) between the two periods statistically defined (year of change of slope)	
	PANORAMIX	STICS
Amiens	-0.008 (1983)	-0.074 (1998)
Bourges	-0.039 (1993)	0.000 (1997)
Dijon	-0.107 (1993)	-0.038 (1999)
Rennes	-0.002 (1993)	-0.001 (1992)
Toulouse	-0.022 (1980)	0.000 (1982)
Nîmes	-0.078 (1988)	-0.016 (1984)
Mean (std)	-0.043 (0.042)	-0.021 (0.030)

Table 3 : Estimation climatic penalty of wheat yield by modeling