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Socio-economic Analysis of the diversity of

Impacts of Public Research for Agriculture

Dissemination of low-input wheat varieties and genetic material from the INRA-AO breeding programme

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INRA manages a long-term programme on bread wheat breeding. This programme has recently been renewed within the framework of co-funded projects with INRA's subsidiary Agri-Obtentions. The reasons for this are include a willingness to maintain public expertise on wheat genetics (wheat being considered as a strategic crop in France) and the need to orient varietal breeding toward new objectives, in line with environmental issues concerning reductions in the use of chemicals and greenhouse gas production. One original output of this programme has been the development of varieties adapted to organic farming, which associate multi-resistance to diseases with an ability to maintain bread-making quality under low nitrogen availability.

Context

With nearly 730 Mt produced worldwide in 2014, wheat represents a major renewable resource for food, feed, and industrial raw materials and globally is the most widely grown crop[7].

With its high yielding wheat production (7t/ha on average in France), the EU28 is the leading wheat producer in the world (145 Mt in 2014) so that its production contributes significantly (22%) to world supply. France alone ranks fifth (37 Mt/year from 5 Mha) in the world and first in the EU for both production and export (with a positive balance of up to $6.7 billion in 2011 and about 58% of its production exported, mostly for milling). Half of the spectacular yield increases observed between 1950 and 1999 have been attributed to genetic improvement, and the other half to so-called "intensification", i.e. increased fertilization (particularly with nitrogen) and the systematic use of chemicals for plant protection against diseases and pests. However, annual yield increases slowed down between 1995 and 2014 in the EU, particularly in the major producing countries of France, Germany, and the UK (Moore and Lobell, 2015). Since 1995, a clear link has been found between yield stagnation and the increasing frequency of limiting climatic factors such as spring droughts during stem elongation, and heat stress around flowering time and during grain filling (Brisson et al 2010). There is therefore an urgent need to accelerate genetic progress for yield potential and yield maintenance, as well as improving tolerance to the abiotic stresses that are expected to increase in frequency and intensity as a consequence of climate change. The intensification of agricultural practices has led to an increasing use of chemical control. France now ranks third in the world for pesticide use and first in Europe, with a total of about 80,000 tonnes of active ingredients sold per year, while cereals account for 40% of pesticide use (Arvalis and UIPP). This situation leads to high production costs, the emergence of resistance to pesticides, and environmental and human health concerns (http://agriculture.gouv.fr/L-utilisation-des-pesticides-en). Moreover, the recent revision of the European Directive 91/414/EC dealing with the marketing authorisations for plant protection products has led to a ban on many active substances, causing technical impasses for chemical crop protection against certain pests. In addition, in France, the Environment Round Table (*"Grenelle de l'Environnement")* targeted a 50% reduction in the use of pesticides by 2018, if this were feasible (Ecophyto 2018 plan[8]). Although the ambitions of Ecophyto 2018 have recently been reduced (a 25% reduction by 2025), the basic trend remains and society continues to demand safer and more environmentally friendly agriculture.

As early as 1980, INRA initiated research programmes to study alternative production systems using fewer inputs, chemicals and fertilizers (see ASIRPA study « Variétés rustiques et itinéraires techniques économes en intrants »[9]). These programmes succeeded in demonstrating that under most conditions, the gross margin (per hectare) of Low Input (LI) farming systems (i.e. production price – input cost) was even better than that of intensive systems. However, these LI production systems are far from being generalized, for two possible reasons:

1) the extreme volatility of wheat prices (and to a lesser extent, of fertilizers) hampers any comparison of gross margins (the average wheat price was €160/t during the period 2008-2014, but ranged from €100 to €280), and their prediction is even more difficult, even though this is an essential element for decision making by farmers. Indeed, it is more cost-effective to adopt conventional systems when wheat prices are above €140/t, but losses may reach €50 to €100/t in years when the wheat price is around €180/t.

2) the gross yield of LI systems is generally 5-10% lower than that of intensive systems, which may be a problem for the whole wheat industry, particularly for export markets when wheat is scarce worldwide and prices are therefore high (2007, 2010, 2013).

We could postulate that current varieties (most bred by private companies) have generally been genetically improved to adapt to HI systems (high N fertilization and fungicide protection), which has long been the main criteria for official registration. The background of the INRA-AO breeding programme was that evaluating selection candidates under LI systems would lead to improved "double performance " varieties (both economic and environmental), and thus help to fill the yield gap between high and low input farming systems.

Inputs and productive configuration

Plant breeding is a core activity of INRA's BAP Division. The wheat programme is as old as or even older than the Institute, which was set up in 1946. Disease-resistance oriented programmes were initiated by the BAP (previously the GAP) Division in the early 1970s in Rennes by Gérard Doussinault and his team. They studied basic resistance mechanisms to several pathogens (rusts, eyespot, fusarium, etc.). These programmes were developed in cooperation with breeding companies, particularly those belonging to the Economic Interest Group (GIE) for Genetic Reseach *(Le Club Cinq)* which was set up in 1983.

Pierre Pluchard started evaluating wheat candidates for LI systems at INRA in Estrées-Mons as early as 1998. This type of management then extended throughout the INRA evaluation network in the early 2000s, either replacing "non-treated" management, or being added as a third management option in some locations (Estrées-Mons, Le Moulon and Rennes).

In the current breeding programme concerning varietal innovation and diversification, 5-year projects since 2006 on crossing and early generation breeding and selection are being carried out by three INRA breeding teams in Clermont-Ferrand (63), Estrées-Mons (80) and Le Rheu (35) and one AO breeder in Orsonville (78). The network of INRA experimental units, and a few sites rented by Agri-Obtentions to cover the majority of wheat-growing regions in France are then used to evaluate late-generation progenies, as described later.

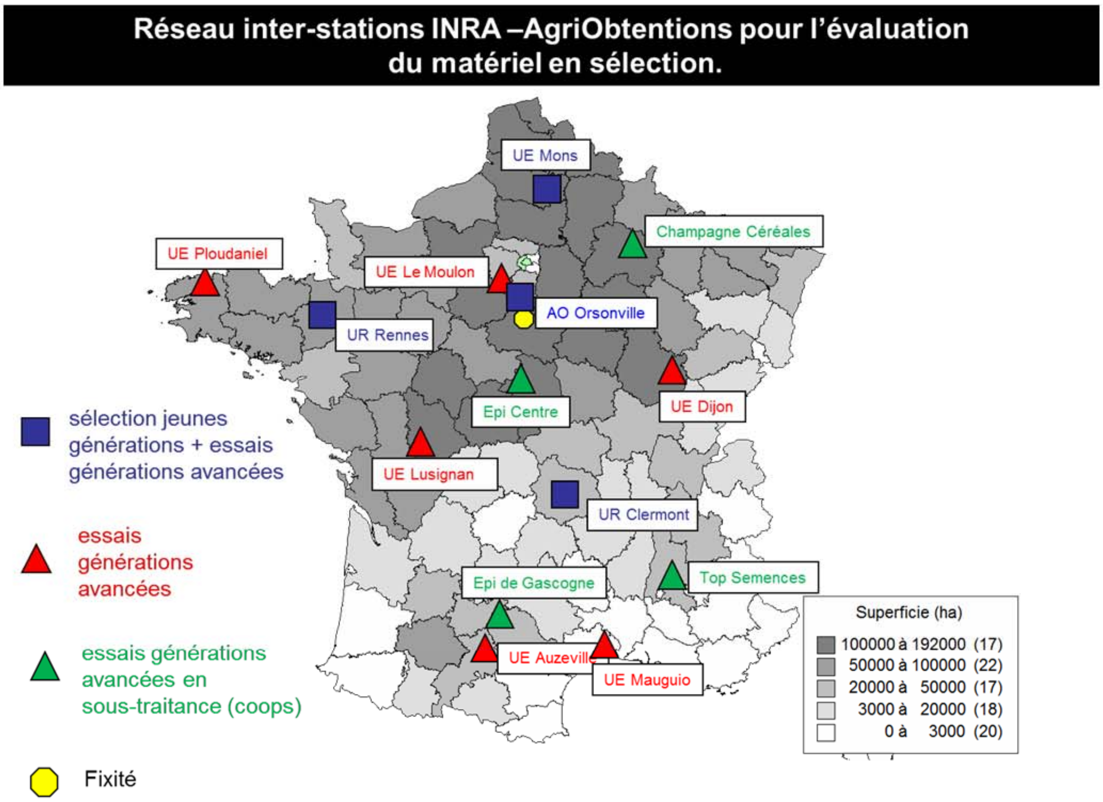

Figure 1: Breeding and evaluation sites belonging to the INRA-Agri-Obtentions network

The knowledge thus generated enabled both INRA and breeders to develop prototypes of multi-resistant varieties such as Rhoazon and Renan (registered by INRA in 1989). This should have encouraged private breeders to follow INRA in the selection of LI adapted varieties. However, this was only partly the case, as we shall see later. Indeed, despite their good results under LI systems (gross margin comparison), the market shares of privately-bred LI varieties (e.g. Oratorio or Balthazar) remained lower than those of more susceptible varieties. Private investment in breeding for LI systems therefore remained limited.

As from 2007, INRA confirmed its orientation towards breeding for sustainable agriculture by setting up 4-5 year funded projects 2007 (# €200,000/year additional funding, excluding salaries). The title of the INRA-AO wheat breeding programme translates into "bread wheat with high economic and environmental performances". This programme draws support from several research programmes, e.g. the ANR-funded protNblé (on nitrogen use efficiency), several FSOV-funded projects on diseases, heat stress, weed competition, etc.

The programme involves nearly 30 staff, representing more than 10 full-time equivalents (scientists, engineers and technicians) in the research and experimental units shown in Figure 1 (red and blue sites). Two groups have been set up: one dedicated to the breeding and selection of varieties and the other to evaluation under LI conditions.

The performance indicators targeted for improvement are:

1. A reduction in the number of chemical treatments (normalized by the authorized dose) and the TFI (Treatment Frequency Index; note that seed coating with fungicide/insecticide is not counted in the TFI). The levers to improve this criterion are mostly the improvement of (durable) genetic resistance/tolerance to fungal diseases and a reduction in plant height to avoid the use of (highly toxic) plant growth regulators. Improving genetic resistance to insects is more difficult, with a few exceptions such as yellow blossom (monogenic) or Hessian fly (rare in France). Particularly, geneticists have few, if any, opportunities to increase resistance against aphids which, in addition to causing direct damage, are vectors of several viral diseases. As far as viruses are concerned, there are some known resistances against mosaic, but no efficient ones against yellow dwarf virus, which is transmitted by aphids in the autumn.

2. A reduction in mineral nitrogen fertilization, which is a source of two pollutants: nitrates in ground (and tap) water and nitrogen oxides, which are greenhouse gases. This pollution is exacerbated if fertilizers are applied when wheat plants are not able to absorb it, i.e. too early or too late as compared to plant growth requirements. But reducing and/or delaying N applications may lead to partial nutrition deficiency. We therefore added a treatment involving fewer N applications (by removing the early spring one) in experiments to evaluate candidates in order to select for tolerance to partial N deficiency. However, in bread wheat, we cannot consider yield alone. Since most wheat is used for milling and baking, end-use quality is of the utmost importance to the market, and thus to the incomes of farmers. This end-use quality is complex, but globally related to grain protein content and composition. For this reason, we also introduced as a selection criterion any deviation (residuals) from the negative regression between yield and protein content, the so-called GPD (Grain Protein Deviation).

The breeding programme is organized along "pedigree breeding" lines, which is a classical scheme used by most breeding companies (see Figure 2).

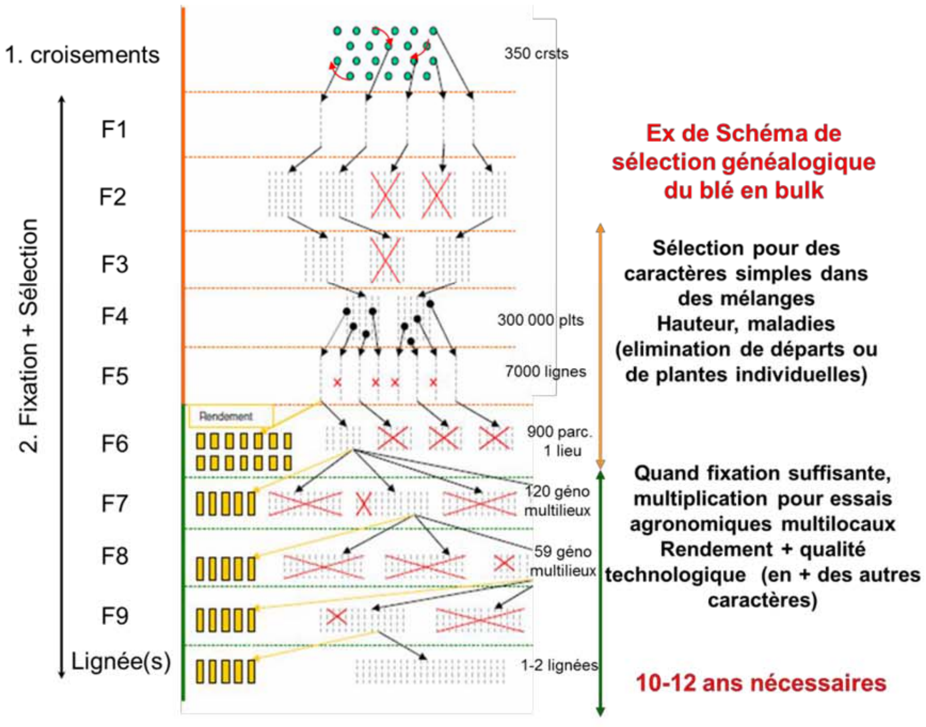

Figure 2: Breeding scheme of the INRA-Agri-Obtentions LI wheat programme

Early generations are grown and harvested as "bulk", with only limited selection on plant height and grain density. It should be noted that Agri-Obtentions subcontracts doubled haploid production on about half of its crosses. This enables a 2-year reduction of the selection cycle by skipping the F2-F3 steps and starting seed increase from DH plantlets at the equivalent of F4 stage. This material is particularly suited to applying genomic selection as implemented in the BREEDWHEAT programme as proof of concept. Selection at the early stages mostly consider overall plant architecture (height, spike fertility, lodging) and disease resistance. This scheme is not specific to the INRA-AO programme and similar schemes are used by most breeding companies.

Once sufficient seeds are available, families derived from single F5 (or DH) plants are grown in micro-plots (5-10 m²), with increasing numbers of locations and replicates when the number of selected candidates decreases. At each location, LI crop management (no fungicides or regulators, reduced N fertilization) is applied to almost half of the replicates (75% in Rennes). Selection is then based on an empirical weighting of yield under intensive and LI management.Late generation evaluations as from F6 are therefore carried out in a multi-site network.

In 2014, F6 and F7 candidate varieties were evaluated under LI systems in half of the trials, carried out at four of the seven locations, and in F8 (pre-registration trials), at seven out of nine sites. This design is original and not used by private companies, which generally focus on High Input (HI) evaluations to meet the demands of most European farmers. However, if the CPTS is really going to adopt environmental criteria for the registration of new varieties (VATE, currently under discussion), private companies will probably adopt schemes similar to INRA-AO to test their candidate breeding lines before registration.

One special case under the LI system is organic farming, where chemical treatments and non-natural mineral fertilization are (theoretically) banned. Only 2% of the French wheat area is grown under organic husbandry, although there are government plans to increase this to 6%. Therefore, private breeders are not really concerned by breeding for specific adaptation to organic husbandry. Faced with this orphan market, organic farmers have to use either conventional French varieties or organic varieties bred in Switzerland or Austria, neither option being fully adapted to their needs. To fill this gap, INRA, as a public research institution, initiated a breeding programme for organic wheat in 2004, led by the Institute for Genetics, the Environment and Plant Protection (IGEPP-UMR) in Rennes. INRA started alone, using personal contacts with organic farmers for evaluations and with the help of ITAB, the Technical Institute for Organic Farming (*Institut Technique de l'Agriculture Biologique*), which provided evaluation sites for free. The main breeding objectives, in addition to those in common with conventional breeding were:

1) Increasing the importance of protein content (GPD), because organic wheat generally has a low protein content, while a minimum threshold is required for bread making;

2) An ability to compete with weeds, mostly by achieving rapid ground cover and a tall size.

This initial success which met the demands of organic farmers, led the French Ministry of Agriculture to ask the CTPS to maintain the Organic Management evaluation network under a long-term funding system.

To enhance the efficiency of INRA's breeding evaluation network for organic management (differing from the official network), INRA recently signed a contract with organic co-operatives (COCEBI and BIOCER) to evaluate the most advanced breeding lines (pre-registration testing).

Research outputs

New hardy wheat varieties have been released by INRA-AO to be raised using LI management systems. They provide a complete genetic and agronomic solution to reducing the environmental footprint of crops while limiting yield losses. LI techniques include a reduced seeding rate and reduced and delayed nitrogen fertilization, which in turn enables a reduction in the use of growth regulators and fungicides. Decision support rules have also been developed by INRA researchers.

In accordance with the selection objectives set for INRA breeding, the varieties obtained by INRA are (Table 1):

- Eleven LI varieties that are resistant to fungi, taller (requiring less growth regulator), more tolerant to partial nitrogen deficiency in spring and resistant to fusariosis;

- Two organic varieties (Skerzzo and Hendrix) that were registered in the French catalogue in 2011. They have a high protein content and yield performances that are similar to conventional varieties under HI systems. These varieties were evaluated by the GEVES in the "conventional" network, but also in a network of four sites managed under organic farming techniques. They offer proof of concept of the efficiency of this programme. Further research is being performed to breed varieties that can compete with weeds in terms of their size and rapid covering ability.

Moreover, the INRA-AO breeding lines are also used as parental lines for private varietal creation (notably hybrids).

	classe technologique	rendement T (% témoins)	rendement NT (% témoins)	bonus CTP	malus CTPS
Koréli (1er CTPS 2005)	BPS	104.8	110.6	faible écart T-NT résistant septoriose	sensible piétin-verse
Barok (1er CTPS 2008)	BAU	106.8	118.9	faible écart T-NT résistant septoriose résistant fusariose résistant froid	-
Folklor (1er CTPS 2010)	BPS	104.7	108.8	résistant septoriose	-
Karillon (2010)	BPS	105.3	107.5	résistant piétin-verse	-
Musik (2010)	BPS	102.2	102.6	résistant piétin-verse résistant mosaïques	-
Lyrik (2011)	BPS	103.2	105.9	faible écart T-NT	-
Hendrix (AgriBio 2011)	BPS adapté à l'agriculture biologique	90.1	93.2	résistant septoriose résistant froid	-
Skerzzo (AgriBio 2011)	BPS adapté à l'agriculture biologique *113% témoins en AB*	91.4	93.9	faible écart T-NT résistant septoriose résistant fusariose GPD++	-
Grapeli (2012)	BAU (soft)	100.9	111	faible écart T-NT	-
Ghayta (2012)	BAF	94.3	96.5	résistant mosaïques GPD++	-
Granamax (2013)	BPS	104.5	113	-	-
Gotik (2014)	BPS	100.6	104.1	résistant septoriose résistant fusariose résistant piétin-verse	-
Gallixe (2014)	BB	102.7	106.3	-	-

Table 1: INRA varieties registered in the French catalogue since 2005

Koreli is the first variety to have truly arisen from the INRA-AO LI breeding programme, and was registered in 2006.

One specific feature of INRA-AO varieties is their good performance under LI systems, which is illustrated by their performance during non-treated (NT) trials, as a percentage of the reference values. The Table only shows the results from official trials with and without fungicide (low nitrogen management is only at an experimental stage, and is not yet included in the official rules for registration). The column in blue in Table 1 presents the LI adaptation traits harboured by the INRA variety. Note that none of the varieties yet contains all the targeted traits, thus justifying the need for INRA to continue investing in wheat breeding. However, the results are even more demonstrative if we look at the results of INRA-AO evaluation network using "true" LI systems (i.e. combining no fungicide with lower nitrogen fertilization and no growth regulator) (see Figure 3).

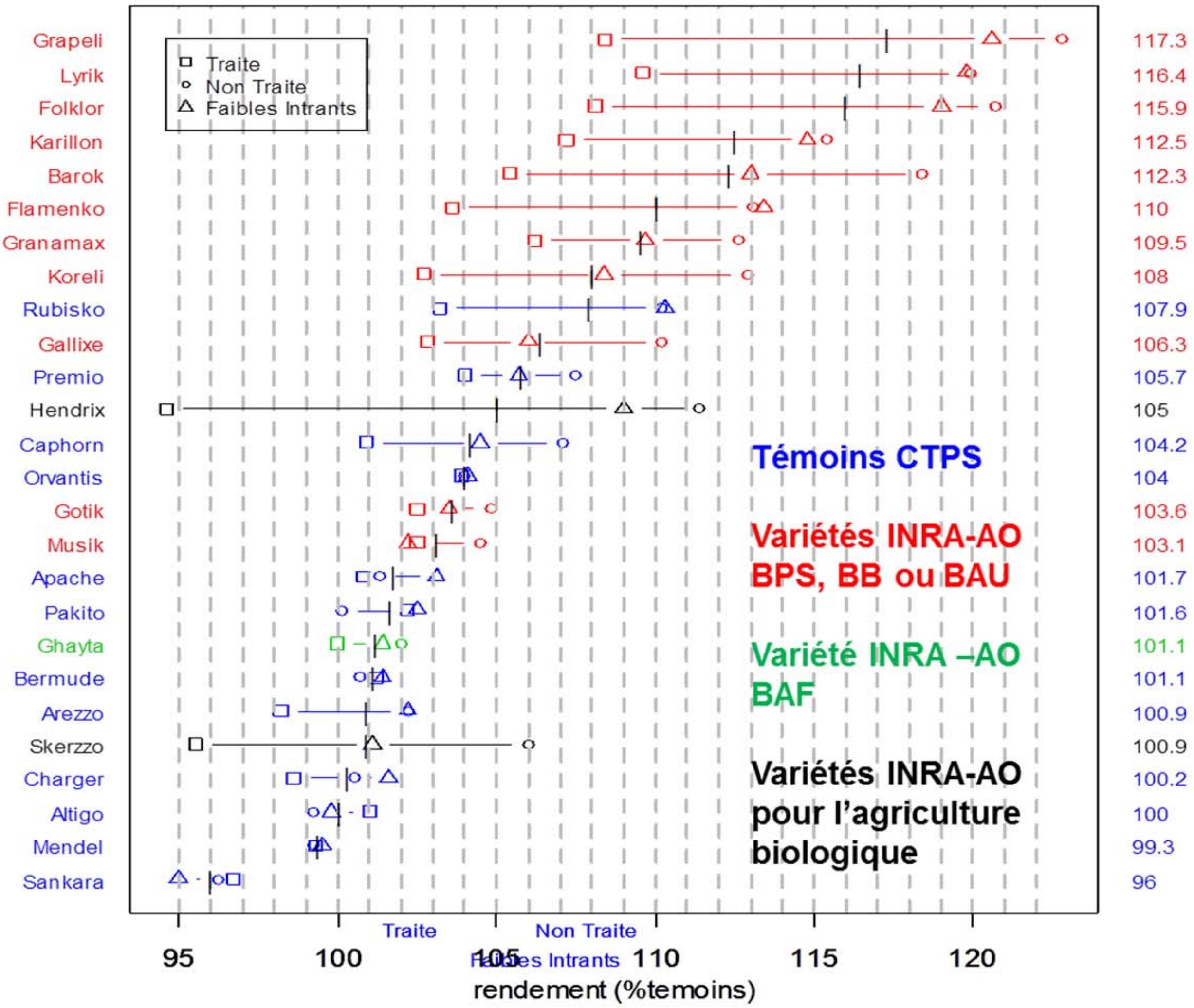

Figure 3: Yield evaluation of INRA-AO varieties in the INRA-AO evaluation network (Figure 1), compared to CTPS reference varieties

INRA-AO LI varieties (in red; high-protein strong wheat in green, and organic varieties in black are not considered) outperform standard reference varieties (in blue) by 11% on average and up to 20% under LI management systems, and by 5% on average and up to 10% under HI management systems. Nevertheless, the reference varieties were the most widely grown varieties at the time of the evaluation: they resulted from older selection schemes so they were often outperformed under HI by the new varieties being evaluated, which are generally not suited for LI-systems. Moreover, under HI conditions, these newly released varieties (which are not shown on the graph) generally had higher yields than AO-LI varieties. This is a consequence of the breeding objectives being taken into account (yield), evaluated under both HI and LI conditions, which is necessary to comply with CTPS registration rules. These varieties are protected by Plant Breeders Rights and were generally jointly bred by INRA and Agri-Obtentions.

Scientific publications

Brisson N, Gate P, Gouache D, Charmet G, Oury F.X, Huard H 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. FIELD CROP RESEARCH 119:201-212

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Bordes J, Goudemand E, Duchalais L, Chevarin L, Oury FX, Heumez E, Lapierre A, Perretant MR, Rolland B, Beghin D, Legouis J, Storlie E, Charmet G, Robert O (2014). Genome-wide association mapping of three important traits using bread wheat elite breeding populations. Mol Breeding (2014) 33:755–768 DOI 10.1007/s11032-013-0004-0.

Charmet G, Storlie E, Oury FX, Laurent V, Beghin D, Chevarin L, Lapierre A, Perretant MR, Rolland B, Heumez E, Duchalais L, Goudemand E, Bordes J, Robert O (2014) Genome-wide prediction of three important traits in bread wheat. Mol Breeding DOI 10.1007/s11032-014-0143-y.

Le Campion A, Oury F-X, Morlais J-Y, Walczak P., Gardet O., Gilles S., Pichard A., Rolland B. (2013). Quelle(s) sélection(s) du blé tendre pour l'agriculture biologique ? Résultats et perspectives d'un comparatif avec les performances variétales en conduite «faibles intrants». Innovations Agronomiques 32, 443-454.

Loyce C, Meynard JM, Bouchard C, Rolland B, Lonnet P, Bataillon P, Bernicot MH, Bonnefoy M, Charrier X, Debote B, Demarquet T, Duperrier B, Félix I, Heddadj D, Leblanc O, Leleu M, Mangin P, Méausoone M, Doussinault G (2012). Growing winter wheat cultivars under different management intensities in France: a multicriteria assessment based on economic, energetic and environmental indicators. Field Crops Research 125:167-178.

Oury F-X, C Godin, A Mailliard, A Chassin, O Gardet, A Giraud, E Heumez, J-Y Morlais, B Rolland, M Rousset, M Trottet, G Charmet (2012). A study of genetic progress due to selection reveals a negative effect of climate change on bread wheat yield in France. Europ. J. Agronomy 40:28-38

Knowledge flow and intermediaries

Agri-Obtentions:

As explained above, Agri-Obtentions is a breeding company with private status that carries out independent breeding programmes on species that have been abandoned by INRA (e.g. barley), or it represents varieties from foreign breeding companies under bilateral agreements. In the case of bread wheat, the INRA and AO programmes are fully integrated, as described above. In addition, AO plays the classic role of a trading company. It aims to develop market share for INRA-AO varieties, implementing specific actions to promote LI systems. It also provides an interface between the needs of farmers and breeders needs and scientific prospects with respect to trait improvement.

INRA and CTPS:

INRA scientists have made important efforts to ensure the registration of LI varieties, despite their lower yield under HI systems. This was achieved by modifying the "technical rules" for variety registration in the French catalogue by the CTPS; for example, by taking account of yield differences between (fungicide) treated and non-treated conditions, or increasing the "bonus" allocated to genetic resistance to disease. The role of Gérard Doussinault (INRA), as Chairman of the cereal section of the CTPS, was crucial, but this "lobbying" needs to continue, even without this chairmanship of the CTPS section, through the active participation of INRA experts in working groups.

The two INRA varieties adapted to organic farming (Skerzzo and Hendrix) are registered as standard "list A" varieties, with the special mention of being "adapted to organic farming". To achieve this result, INRA negotiated with the GEVES and CTPS to obtain: 1) the possibility to carry out a special evaluation under organic management, and 2) that experts should consider the results of trials under organic management in order to balance the lower yield obtained under conventional conditions. In 2006, the work done by INRA on protein content also led to the adoption of GPD as an official criterion in the CTPS technical rules for the registration of new varieties. This GPD criterion increased the overall importance of protein content in registration decisions and then facilitated the registration of varieties adapted to organic farming.

Chambers of Agriculture:

The low input network established by JM Meynard (INRA) in the early 1990s is still active, based on the voluntary contribution of several Chambers of Agriculture and is coordinated by INRA (B Rolland). Technicians from Chambers of Agriculture maintain close relationships with farmers who have adopted the LI system, which thus facilitates the local promotion of these systems.

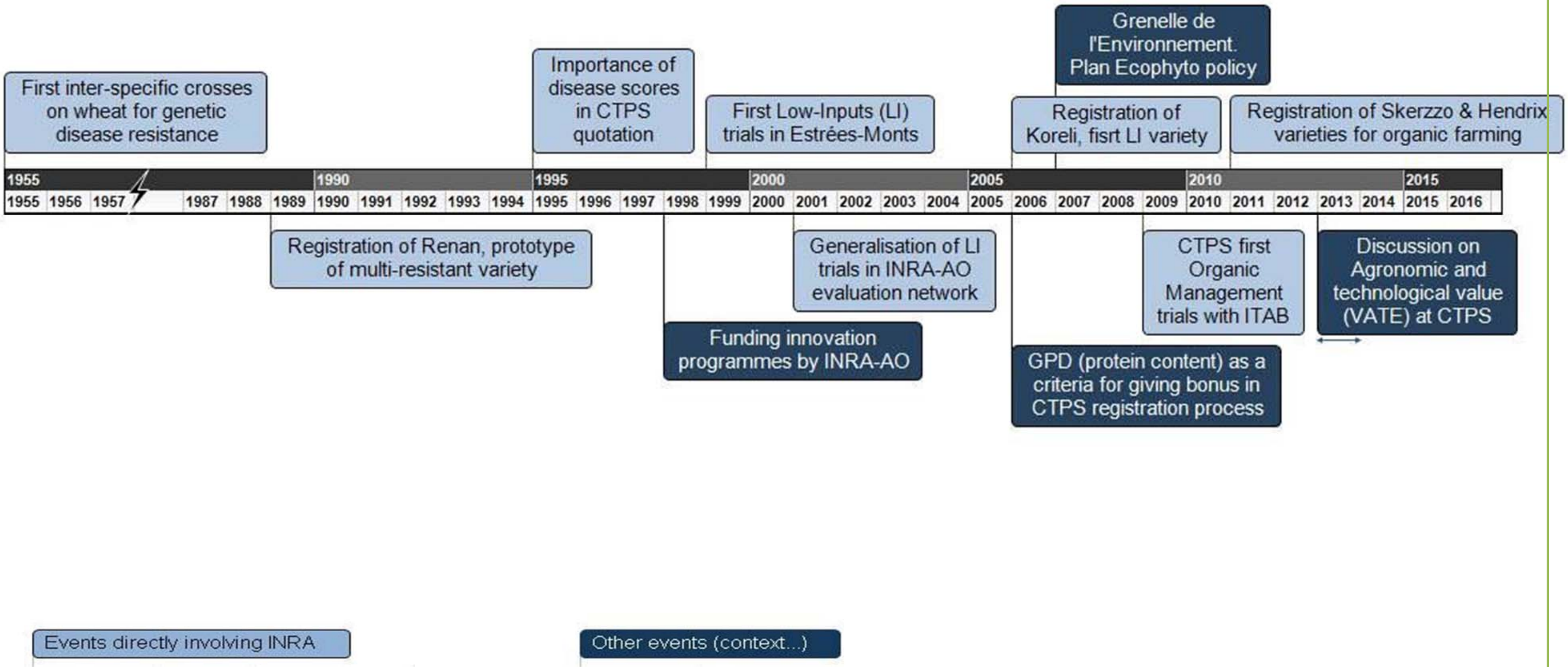
ITAB: Technical Institute for Organic Farming:

Responsibility for the first "official" trials carried out by the GEVES was taken by the ITAB, free of charge. Indeed, it was important to have these first two varieties registered with the mention "adapted to organic farming". However, ITAB has a small funding capacity, and for subsequent "official" organic experiments, a permanent system of funding needed to be established. At a later stage, the ITAB offered strong support for the first official evaluation for CTPS by taking responsibility for several trials in organic farming (on actual organic farms).

Saaten Union:

This company is currently the only one selling hybrid seeds; it signed an agreement in this respect with Agri-Obtentions in 2003. Saaten Union is able to freely use the most advanced INRA-AO breeding lines to produce experimental hybrids. If a hybrid is registered and the seeds are sold, the royalties are shared as follows: 25% for the supplier of each parent, and 50% for the entity carrying out hybridisation, i.e. Saaten Union. It is likely that similar agreements have been concluded between Saaten Union and other seed companies.

Chronology


First inter-specific crosses on wheat for genetic disease resistance
Importance of disease scores in CTPS quotation
First Low-Inputs (LI) trials in Estrées-Monts
Grenelle de l'Environnement. Plan Ecophyto policy
Registration of Koreli, fisrt LI variety
Registration of Skerzzo & Hendrix varieties for organic farming
1955 1990 1995 2000 2005 2010 2015
1955 1956 1957 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016
Registration of Renan, prototype of multi-resistant variety
Generalisation of LI trials in INRA-AO evaluation network
CTPS first Organic Management trials with ITAB
Discussion on Agronomic and technological value (VATE) at CTPS
Funding innovation programmes by INRA-AO
GPD (protein content) as a criteria for giving bonus in CTPS registration process
Events directly involving INRA
Other events (context...)

Impacts 1

Dissemination of INRA-AO LI varieties:

The LI varieties available in France include the LI varieties bred by INRA-AO (in dark blue in Table 2), private LI hybrid varieties created using INRA-AO parental lines (light blue), and private LI varieties from private breeding schemes (red).

During 2008-2013, the market share of INRA-AO varieties among all wheat varieties in France rose from 3.1% to 6.5% (5.5% in 2015 see Figure 4) .

Table 2: Surface areas in France of multiplication for the principal LI varieties: 2011-2015

	2011	2012	2013	2014	2015
Apache (1997)	5856	5714	4240	3788	
Bermude (2006)	2564	1888	1242	1081	
Arezzo (2007)	4668	4555	4988	4491	
Solehio (2008)	1165	1557	1791	2098	
Rubisko (2011)	-	916	5052	6184	
Cellule (2011)	-	721	2092	3471	
Oregrain (2011)	-	137	651	1938	
Ambition (2005)	309	264	191	192	
Azzerti (2009)	400	286	384	235	
Mathéo (2012)	-	-	228	542	
Oxebo (2009)	543	279	269	228	
Koréli (1er 2005)	**1481**	**1251**	**921**	**270**	**120**
Barok (1er 2008)	**1277**	**1593**	**1462**	**1125**	**620**
Folklor (1er 2010)	**360**	**148**	**123**	**52**	**31**
Karillon (2010)	**309**	**210**	**39**	**12**	**0**
Musik (2010)	**417**	**982**	**522**	**433**	**258**
Lyrik (2011)	**-**	**243**	**265**	**758**	**1084**
Hendrix (AgriBio 2011)	**-**	**27**	**36**	**37**	**43**
Skerzzo (AgriBio 2011)	**-**	**3**	**86**	**102**	**139**
Grapeli (2012)	**-**	**-**	**68**	**391**	**574**
Ghayta (2012)	**-**	**-**	**61**	**156**	**185**
Granamax (2013)	**-**	**-**	**-**	**359**	**460**
Gotik (2014)	**-**	**-**	**-**	**-**	**78**
Gallixe (2014)	**-**	**-**	**-**	**-**	**61**
Hyfi (hybride 2012)	**-**	**-**	**785**	**1881**	**2250**
Hylux (hybride 2012)	**-**	**-**	**2**	**93**	**160**
Hypod (hybrid 2012)	**-**	**-**	**19**	**154**	**0**
Hybiza (hybride 2013)	**-**	**-**	**-**	**94**	**378**
Total France	**80439**	**83858**	**86780**	**96343**	

Témoins CTPS Variétés rustiques du privé Variétés INRA-AO Hybrides avec parent(s) INRA-AO

Black=CTPS reference varieties, Red=private LI varieties, Dark Blue= INRA-AO LI varieties, Light Blue= private LI hybrids.

We observed that the privately bred varieties that could be considered as being adapted to LI management (mostly because of their disease resistance) are multiplied less than INRA-AO varieties. Indeed, varieties resulting from INRA material (AO-varieties+hybrids) account for almost 80% of the French area sown to the principal LI varieties. However, no official statistics are available, and it is very difficult to obtain market figures variety by variety from the companies concerned (interview with cooperative).

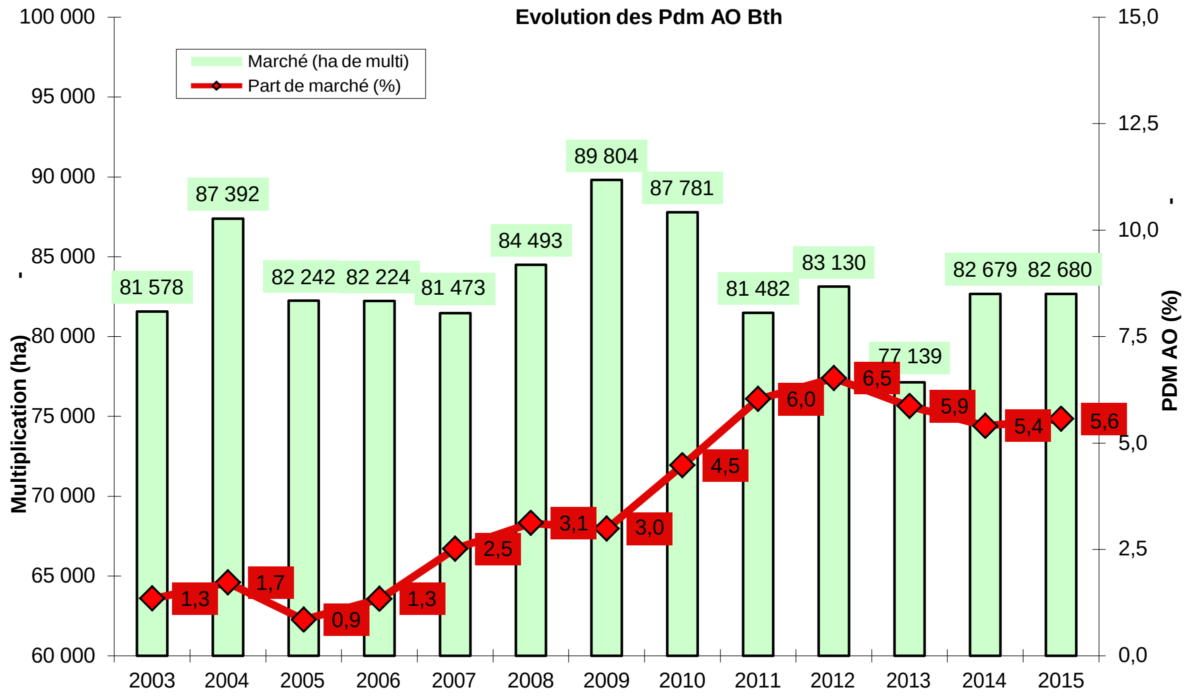


Figure 4: Evolution of the market-share of all INRA-AO LI varieties (2003-2015)

Of course, INRA-AO LI varieties could never take a 100% market share. However, private companies may follow the way opened by INRA and introduce LI adaptation into their selection criteria. And indeed, INRA's genetic material is also stimulating the creation of private LI varieties. In fact, it should be noted that INRA-AO LI varieties can be used as genitors in private breeding crosses and hybrid creation (see the four hybrid varieties created by Saaten Union based on INRA-AO material, shown in light blue in Table 2). Although pedigree information is no longer publicly available, it is possible to guess these data based on coancestry coefficients inferred from market data. We did not perform a detailed analysis, but, for example, 141 French varieties display a coancestry coefficient with cv Barok (the most widely grown INRA LI variety, although not suited for bread-making) of >0.25, a threshold for a half sib (one common parent) or grand parent/daughter. This indicates that Barok and private varieties share common parents, or perhaps that Barok has already been used by breeding companies to transfer traits for adaptation to LI management to their breeding germplasm and future varieties. Likewise, the private LI variety Boregar (raised on 60,000 ha in 2014) displays coancestry of >0.25 with Renan, the first multi-resistant INRA variety registered in 1999. This raises hopes that LI systems could become more widespread in the near future without any yield loss, but with economic and environmental benefits. For more recent INRA-AO LI varieties, it is too early to see their progeny, if any, registered as new varieties, because of the length of this process (8-10 years). As illustrated in Table 3, INRA-AO LI varieties are suited for LI systems. Table 3 illustrates the varietal recommendations for Normandy (a region where INRA varieties fit the requirements for climate adaptation). Indeed INRA varieties (in green) are considered to be "good and regular" under LI systems.

Table 3: Recommended varieties in the Normandy low input network

System **Average yield**	**Conventional system**	**LI system**
Regular - good	Fluor, Lyric, Cellule, Grapeli	Fluor, Lyric, Cellule, Grapeli, Folklor
Irregular – mean to good		Tobak
Regular - mean	Rubisko	Arezzo, Rubisko
Very irregular	Tobak, Ronsard	Ronsard
Regular - low	Arezzo, Folklor, Pakito	Pakito

Despite these recommendations, LI varieties are also raised under conventional systems (and vice-versa: for example, we know that Cellule and Rubisko, two high yielding varieties in conventional farming, are also often used in reduced input systems). In fact, the relative success of INRA "low-input" varieties is partly due to their good performance under high input farming systems, but also to an increasing willingness of farmers to reduce their use of pesticides, either for economic reasons (highly sensitive to wheat prices), safety reasons (farmer's health) or environmental issues, or nitrogen application (economic reasons, water safety regulations, etc.). **The total area grown using LI varieties (private and AO varieties + hybrids) in France reached 289,000 ha in 2014, which accounted for 5.8% of the total French wheat acreage**. We do not know the precise share of LI systems in that surface area.

Recently, Institutes such as Arvalis and advisory bodies such as cooperative groups (e.g. Visvescia) have oriented their recommendations towards the use of LI varieties. For example, in Perspectives Agricoles (n° 422, March 2015), we found:

"I.F.: For the past twenty years, the soft wheat varieties registered in the French catalogue have become increasingly tolerant of diseases. A synthesis of the results obtained by the network covering a region stretching from Brittany to Burgundy has show that recently registered varieties are amongst the best performing under low input management systems. This is the case, for example, of the ***Lyrik and Grapeli*** *cluster in Brittany,* ***Lyrik, Folklor*** *and Attlass in Normandy,* ***Lyrik*** *and Rubisko in the Ile-de-France region around Paris or Oregrain and Ascott in the Poitou region."*

Several INRA-AO varieties (in bold type) are referenced for use under LI systems.

Economic

LI varieties raised under conventional systems enable yield gains:

Raised under conventional farming, INRA-AO LI varieties can offer an average yield gain of 5% (i.e. 0.35 t/ha) over the most widely grown varieties. At an average price of €160/t, the associated **annual gains amount to €56/ha**.

Raised under LI-systems, LI varieties would at best maintain yields and enable reductions in input costs:

Previous results from the INRA Chambers of Agriculture "low input network" compared conventional and LI management systems. LI systems enabled a reduction in fungicide treatment of 1 (# €45) and nitrogen of 20 Kg/ha (# €15). The low input network tested a majority of varieties from private companies, considered as best suited for LI management, but not specifically bred for this purpose. They thus recorded yield losses when compared to conventional systems and found that the balance between reduced yield and reduced input costs ranged from + €50/ha to - €207/ha during the past 12 years, this trend becoming negative since 2012, related to high wheat prices in the market. On average, the difference was # -€20, to the detriment of LI systems (thus making it more profitable to apply nitrogen and fungicides to gain marginal yield and explaining why these LI systems have been poorly adopted to date). However, genetic differences do exist regarding yield loss under LI and conventional systems, and we can anticipate that the yield of INRA-AO LI varieties specifically bred for LI systems should be comparable to the yield of the mostly widely grown conventional varieties used under conventional systems. The gain in gross margin achieved by using INRA varieties should therefore be regularly positive. Considering that INRA-AO LI varieties raised under LI systems enable treatment savings of # €60/ha while maintaining constant yield, this results in an **annual gain of €60/ha**.

INRA-AO LI varieties can thus achieve an annual gain of # €60/ha when raised under conventional or LI systems. The yearly cultivation of INRA-AO varieties on # 190,000 ha in France since 2011 has resulted in **gains of €11.2 M/year for farmers** (**€57.7 M cumulated over 2011-2015**). Considering these yearly gains to be fixed, the economic surplus would reach €160 M over a 20-year period (with a discount rate of 4%).

Apart from these direct benefits for farmers, the genetic material supplied by INRA to Saaten Union also enables the generation of economic gains for breeders, multipliers and farmers. The turnover generated by Saaten Union on these varieties (# €1.3 M cumulated over 2013-2015) thus underestimates these gains.

Environmental

Very few statistics exist regarding the use of LI systems. Firstly, there is no clear definition of a “low input system”. Instead, different scales of input reduction, encompassing nitrogen, growth regulators and chemicals, are used by scientists (for instance, matching of the Meynard et al[10] and Butault et al[11] classifications of systems is ITK1=N0= intensive or High Inputs, ITK2=N1=conventional, ITK3= N2a and N2c=Low Inputs, N3=Organic). Nonetheless, LI systems recommend reducing nitrogen fertilization by 30 kg/ha and no fertilization after the winter, no growth regulators and a single fungicide treatment. By comparison, conventional systems allow for three treatments for nitrogen fertilization at a level calculated using forecast balances, one treatment with growth regulator and up to two fungicide treatments.

The "aggregates" found in statistical reports are also usually too large (e.g. “crop”, not even wheat, and a fortiori no fate by variety). Overall, the Ecophyto report highlighted the fact that LI practices are scarce[12].

However, there has been a trend towards a paradigm shift through extension services (mostly associated with co- operative groups). For the period of a few years, they have taken account in their recommendations of the robustness of varieties against disease, so as to save one fungicide application (despite the fact that their group sells pesticides). This trend is on a virtuous pathway towards the adoption of LI systems, although this may take some considerable time. A complete technical solution comprising both LI varieties and their corresponding adapted LI management practices is now available. Therefore, a strong potential effect on the environment is now mostly dependent on global wheat prices.

Although farmers do not apply all the recommendations made by INRA regarding LI management, they are gradually starting to adopt some of them.

Figure 5: Evolution of the proportion of arable farms involved in the DEPHY system, according to their level of pesticide consumption

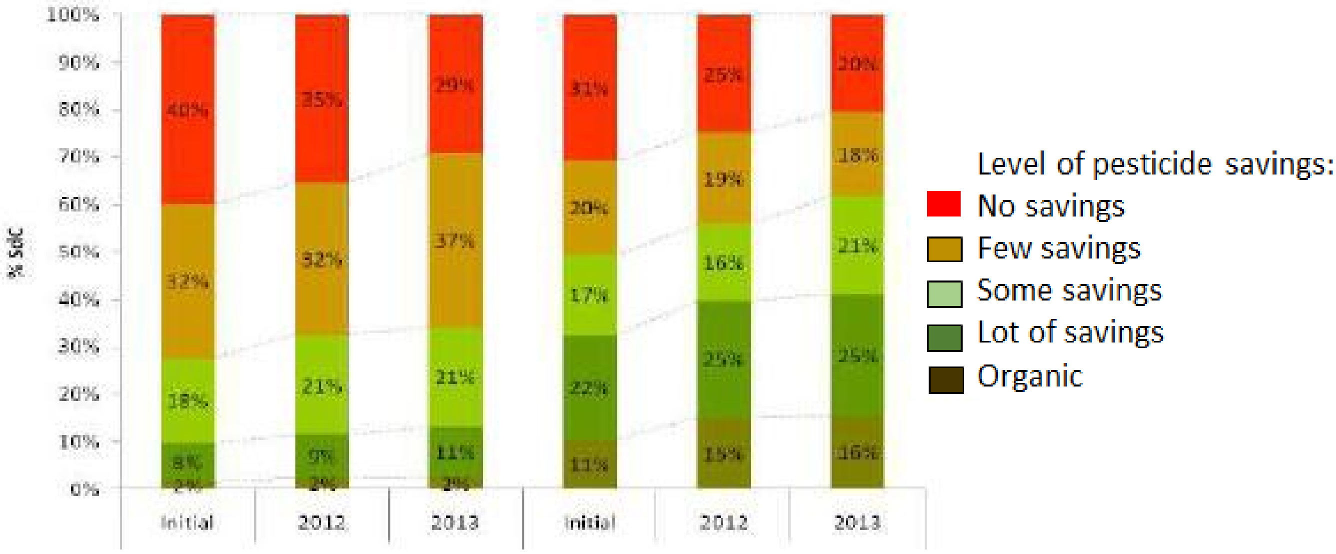
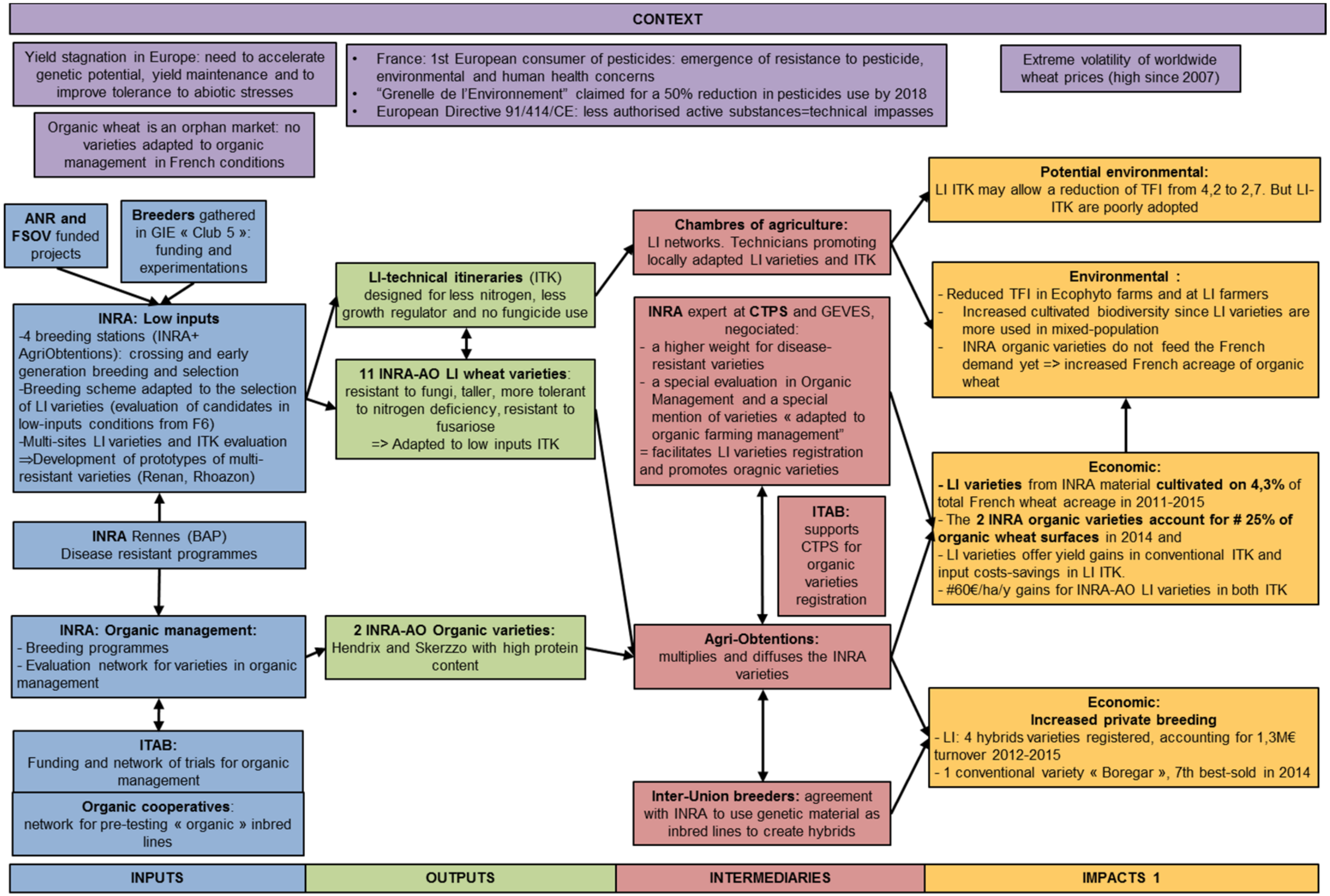


Figure 5 describes the adoption of “low input systems” (in green) by arable farmers working the 451 farms that have been involved in the French Ecophyto-DEPHY programme since 2008. The proportion of eco-friendly farmers (three shades of green) rose from 28% to 34%. On these farms, the average TFI of field crops fell by 12% between initiation of the DEPHY network and 2013[13]. Moreover, even in conventional farming, “highest inputs” systems have regressed from 40% to 29% during the past 5 years, and the average Total Frequency Index for cereals fell from 6.2 to 5.8 during the 2006-2011 period[14].

As for organic farming, the varieties released by INRA are the first in France (there are German varieties adapted to organic farming but they perform less well than the INRA varieties). To date, no private company has applied to register varieties adapted to organic farming. Within a few years, Skerzzo has become the fourth most widely used variety for organic farming, which is notable since the turnover of varieties is much longer under organic management than in conventional agriculture. The two INRA varieties bred for organic management account for # 25% of the varieties used by French organic farmers, and the total French demand for organic varieties was not met in 2014: organic farmers found it necessary to use conventional varieties under organic management. The organic varieties created by INRA have thus facilitated the development of organic farming and probably contributed to increasing the total French wheat area cultivated organically (80,000 tonnes of organic grain were collected in France in 2011, and 96,000 t in 2012[15]).

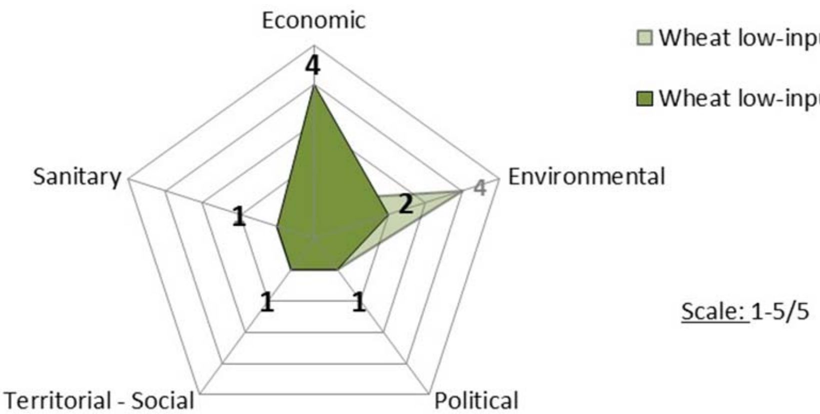
As well as enabling a reduction in pesticide use, LI varieties can enhance biodiversity in agrosystem by favouring the use of mixtures of varieties rather than single genotypes. However, we lack statistical data on the extension of such mixtures. Ongoing projects (e.g. ANR wheatamix: http://www6.inra.fr/wheatamix) will probably provide more information in this area.

Impact pathway



Impact vector

Impact dimension	Importance	
Economic	4 / 5	**INRA varieties:** - **INRA-AO LI varieties** accounted for **# 6%** of the total French wheat market in 2011-2015 - The two **INRA organic varieties accounted for # 25% of organic wheat surfaces** in 2014 - LI varieties from INRA-AO can offer an **annual gain of €60/ha** under conventional or LI systems => **€57.7 M** economic surplus in 2011-2015 in France **Privately bred varieties:** - LI: four hybrid varieties registered, accounting for turnover worth €1.3 M in 2012-2015 - One conventional variety, "Boregar", the 7th best-seller in 2014, is a half-sib of the INRA Renan variety
Environmental	2 / 5 Potentially 4 / 5	First two French wheat varieties adapted to organic farming LI varieties are likely to be used more frequently in varietal blends than other varieties. Small reduction in TFI: LI varieties are generally adopted for conventional management.



Data sources

<u>**Bibliographic resources mobilized:**</u>

Several official reports found on www.gouv.fr

<u>**List of interviews conducted:**</u>

- Damien Rousseau, Vivescia
- Savine Oustrain, Vivescia
- Erwan Olivier, Limagrain
- Joel Blot, Agri-Obtentions
- Bernard Rolland, INRA UMR IGEPP
- Aude Barbottin, INRA UMR Agronomie