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ANALYSIS

Why are ecological, low-input, multi-resistant wheat cultivars slow to develop commercially? A Belgian agricultural 'lock-in' case study

Gaëtan Vanloqueren, Philippe V. Baret*

Department of Applied Biology and Agricultural Productions, Université catholique de Louvain, Belgium

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ABSTRACT

The use of multi-resistant cultivars allows a significant reduction in fungicide use in low-input cropping systems. However, many major wheat cultivars used in Europe remain sensitive to frequent diseases and require fungicide protection. This paper aims at understanding the factors explaining the low level of adoption of multi-resistant wheat cultivars in Wallonia (Belgium). Cultivar adoption has been an important topic of research, but few analyses have been done in Europe in the past decades. We used a systems approach combining a survey among stakeholders in the food chain and a systematic analysis of the publications of extension services. We identified twelve factors impeding wider adoption of multi-resistant cultivars. These factors explain why current wheat-cropping systems are maintained in a 'pesticide lock-in' situation, an economic concept that could be used more frequently to study agricultural innovations. Considering these intangible 'barriers' to current and forthcoming innovations is a first step towards a more comprehensive policy to promote sustainable agriculture. Similarities between Wallonia and France are discussed and methods of promoting wide use of resistant cultivars are proposed.

1. Introduction

Disease-resistant cultivars have been bred throughout the world for a long time and are numerous among commercially available wheat cultivars. Their advantages for producers are, first, a direct economic benefit (the reduced costs of fungicides and fuel due to a reduced need for fungicide applications) and, secondly, an indirect social amenity (reduced time and hassle devoted to the control of crop health and to spraying). These two benefits are of greater importance when cereal prices are low (low prices make the application of fungicide less cost-efficient) and, to a lesser extent, for farms which are expanding in size with a constant workforce. These were two of the main current trends of cereal production in Europe when this research was conducted. Wheat prices in Belgium were as high as 226 €/T in 1983 (Conseil Supérieur Wallon de l'Agriculture, 2002) but decreased thereafter, dropping below 100 €/T in 2004–05.

While the main benefits of disease-resistant cultivars are for farmers, society as a whole has a lot to gain from them as they contribute to a general reduction in pesticide use, which is recognised as a significant and worthwhile public objective because of the environmental and health problems linked to the use of pesticides (Wilson and Tisdell, 2001). However,

* *Corresponding author*. Unité GENA, Croix du Sud 2 boite 14, B-1348 Louvain-la-Neuve, Belgium. Tel.: +32 10 47 37 23; fax: +32 10 47 37 28.
E-mail address: vanloqueren@gena.ucl.ac.be (G. Vanloqueren).

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disease-resistant cultivars do not systematically become best-selling cultivars. On the contrary, many best-selling cultivars prove to be weakly resistant to one or more important diseases, and rely completely on fungicide protection. Why do disease-resistant cultivars fail to reach the top? Is the yield lag between the hardiest disease-resistant cultivars and the highest-yielding cultivars the only explanatory factor for this, as the analysis of the 'yield penalties' of disease resistance in plants may lead us to conclude (Brown, 2002)?

The aim of this study is to understand all the factors impeding the use of the best disease-resistant cultivars by farmers. We tackled this objective with a case study focusing on one cereal, winter wheat, in one specific European region, the cereal-growing part of Wallonia (Belgium).

Winter wheat is the main cereal in Wallonia, comprising 70% of the area devoted to cereals, with a mean yield of 8.5 t/ha. Some 8000 farmers grow winter wheat on 130 000 ha. Most of the winter wheat is grown under a conventional high-input cropping system, with the exception of organic wheat and low-input systems under agri-environmental schemes for which a premium is given (requiring reduced sowing density, use of maximum one fungicide application, no use of straw shorteners, greater attention to cultivar choice and fertilisation). Each of these two exceptions represents about 1% of the wheat surface. Wheat is used for animal feed, human consumption and the starch industry.

The most problematic diseases in the wheat cropping systems under consideration are *Septoria* leaf blight (SLB), brown and yellow rusts, powdery mildew and, more recently, *Fusarium* head blight (FHB) (Smith et al., 1988; Lucas, 1998; FUSAG and CRA-W, 2005). SLB has an important economic impact on wheat production (yield and quality). It is caused by *S. nodorum* and *S. tritici* and its impact has become more pronounced in recent years, due in part to the increased genetic resistance of wheat to other foliar pathogens such as powdery mildew (Eyal, 1999). FHB is a cyclic disease, occurring once every 3 to 5 years (Champeil et al., 2004a). Once a limited disease, to which no particular attention was paid in the region, FHB gradually became a major public concern as data on the public health problems associated with fusariotoxins, especially deoxynivalenol (DON), accumulated. FHB occurs in many regions of the world with yield losses reaching 50% under unfavourable conditions (Parry et al., 1995). Yield losses are limited in Wallonia, but mycotoxin contaminations are a major concern in unfavourable years such as 2002, when over 35% of the samples analysed exceeded the EC recommended DON level (Chandelier et al., 2003b). Maximal DON levels vary depending upon the final use of the grain: baby food, human food or animal feed.

Fungicide applications differ from one plot to another according to agro-meteorological conditions, pathogen epidemics and the crop cultivar, as well as the farmer's objectives and aversion to risk. Average quantities of the active ingredients for wheat were reduced during the period 1991–2000: the total quantity of crop protection products dropped from 4.7 to 3.2 kg/ha and the quantity of fungicides from 1.7 to 0.7 kg/ha (Ministère des Classes Moyennes et de l'Agriculture, 2002). However, the cost of crop protection rose from 124 to 162 €/ha between 1994/95 and 2000/01 (Groupe de travail de la filière 'Céréales', 2003). Farmers make between one and three fungicide applications a year (usually one or two) and each application generally consists of mixtures of fungicides, mainly triazoles and strobilurins.

Fungicides for both diseases are problematic. The appearance of *Septoria* populations resistant to strobilurins fungicides has been rapid and has occurred on a European scale. In a three year period, the effectiveness of this new active ingredient decreased so markedly that it is now advised to use it only in mixtures with other substances (Moreau, 2004). Fungicide applications for FHB are only weakly effective: applications must be made during the very short flowering period, when kernels are sensitive, which allows the farmers only limited flexibility. Even the best active ingredients only control disease incidence by half (Chandelier et al., 2003a). In certain cases fungicide applications can even stimulate mycotoxin production. This has led scientists to advise that mixtures of fungicides should be applied (European Mycotoxin Awareness Network, 2005).

In 2004, eighty cultivars were bred in Belgium, of which 44 cultivars were registered on the Belgian national cultivar catalogue (Ministère de l'Agriculture, 2005) while the others were available through the European cultivar catalogue. The public extension services in Wallonia conducted field tests on a great number of these cultivars: in 2004, 52 were assessed in the *Livre Blanc sur les Céréales* (White Book on Cereals, see below) for basic characteristics such as yield or phytosanitary contribution to yield (rate of 'loss' of untreated plot against treated plot, in percentage of kg/ha).

The extension services conducted a further analysis of 24 'main' or 'recommended' cultivars (only 11 of which are included in the Belgian catalogue). Additional information, such as cultivar susceptibility to diseases, is available to farmers for these cultivars. Scores for cultivar resistance to diseases are a synthesis of data from experimental fields and visual observations in farmers' fields. Four levels of resistance are determined (with 4 being the highest resistance) for each of the four most common diseases (FHB, SLB, brown rust, yellow rust). In the present paper, we define levels 1 and 2 as 'poor' and 'low' resistance respectively, while we speak of resistant cultivars for levels 3 and 4. In 2004, twelve out of the 24 main cultivars had poor or low resistance to SLB and five to FHB. Only six were multi-resistant (level 3 or 4 for each of the four common diseases). These cultivars accounted for 26 to 31% of the official seed propagation areas in Belgium between 2003 and 2005.

Section 1 of this paper presents the systems approach we employed. Section 2 describes the twelve factors explaining the weak adoption of existing multi-resistant cultivars. In the discussion section, our Belgian findings are discussed in comparison with neighbouring France, and with the help of the 'pesticide lock-in' concept. Possible ways of changing the situation are also discussed.

2. Method

Our qualitative and multidisciplinary approach is one of a number of soft-systems approaches (Checkland, 1981; Ison et al., 1997). Soft-systems approaches are useful to understand and integrate agronomical, socio-economic and organisational dimensions of complex problems. While the method is used here to study technology adoption, its principles have also been used to tackle other complex problems such as why and when food systems fail to deliver safe products (Hennessy et al., 2003) or to discover impediments to the development and use of non-chemical alternative strategies to pesticides (Diamand, 2003).

Our method comprises three methodological steps. First, a survey of stakeholders in the cereal agricultural sector and food chain was conducted in Wallonia during the 2004/05 winter. It consisted of 25 in-depth semi-directed interviews. Technical advisers from public extension services, employees of private firms and scientists were interviewed about FHB and SLB. The survey was conducted according to the '*de proche en proche*' ('friends of friends') method (Blanchet and Gotman, 2001), which aims at interviewing influential stakeholders rather than statistically representative samples. In this method, the people interviewed are questioned about who are the most relevant stakeholders for the issue under consideration. Only the most frequently mentioned people are then interviewed. In our case, we stopped the survey when new interviews were not bringing any new information. For farmers, we took account of the results of a larger survey among a hundred farmers in the cereal-growing region of Wallonia, which gave useful results on farmers' decision-making processes (Marot et al., 2005).

The questions in the survey were directed at understanding the use of several integrated pest-management strategies. However this paper focuses solely on the use of disease-resistant cultivar. Semi-directed interviews were based on a series of questions common to all interviews, but allowed for secondary, in-depth questions that depended on the answers being given by the interviewee. Examples of questions raised in all interviews are: What are the current agricultural strategies available to stop or reduce these diseases? How far do farmers use them? Why do farmers not use disease-resistant cultivars? Is the situation of disease-resistant cultivars different from a few years ago? Why? Examples of specific questions are: (to breeders and seed companies) What are your priorities for breeding programmes? (to scientists) What kind of research projects on disease control have been conducted in the past, and are being conducted currently?

Secondly, the contents of the *Livre Blanc sur les céréales* (White Book on Cereals), a bi-annual handbook published by public research institutions and extension services, was analysed for the period 2000 to 2005 (FUSAG and CRA-W, 2005). The *Livre Blanc* is the main written source of independent technical advice for wheat producers in Wallonia. The Gembloux Agricultural University (FUSAG) and the Wallonia Agricultural Research Centre (CRA-W) edit it. This bi-annual handbook is composed of regular papers updating the technical advice on main themes, and occasional shorter papers on current issues. The main purpose of the handbook is to popularise results from the latest research and give the best science-based advice to farmers.

The 125 published papers in the period 2000 to 2005 were first classified according to their main subject, such as 'fertilisation', 'wheat quality', 'weeds', etc. All papers related directly or indirectly to diseases and crop protection were selected: these included regular papers (up to 60 pages long) on 'wheat crop protection' and 'fungicides' as well as occasional shorter papers on 'head blight and mycotoxins', 'wheat cultivars and diseases', 'organic wheat' and 'agri-environmental schemes'. The 31 selected papers accounted for 43% of the total pages of the publications during the period, and contained 205 tables presenting results from experimental research carried out on research sites or on-farm experiments in Wallonia during this period. These tables were systematically analysed (see Table 2).

Thirdly, a desktop search for grey literature from the cereal sector and a literature review covering the various domains involved completed our research. The combination of these different sources allowed us to compile information about how cereal production functions from existing experimental research as well as from the human experience of a diversity of professional stakeholders. It enabled us to take into account qualitative as well as quantitative aspects, and to crosscheck and verify the results obtained, for example by analysing technical data in the light of the 'real world'.

3. Results

Our approach uncovered twelve factors impeding a broader use of multi-resistant wheat cultivars (see Table 1). These factors are technical and socio-economic, obvious and less obvious. They are grouped according to the level of the agri-food chain at which they exert an influence: farmers, the market, public extension services and research, public regulation and past agricultural policies.

Several factors are direct adoption factors that have a direct influence on farmers' adoption of multi-resistant cultivars. Others, such as Factors 6 and 10, are indirect determinants of innovation that influence the scientific and commercial development of quality multi-resistant cultivars.

Table 1 – Factors impeding the systematic use of multi-resistant wheat cultivars

Farmers
1) Direct cultivar choice criteria of farmers: disease resistance comes only after gross yield, resistance to lodging and commercial quality
2) Incomplete resistance of resistant cultivars and the unpredictability of epidemic development
3) Limited number of cultivars resistant to all frequent diseases
Market
4) Contradictory objectives of crop protection and seed departments in supply companies (which disadvantages resistant cultivars)
5) Influence of supply companies' salespeople on farmers' practices
6) Breeding history and breeding objectives of seed companies
Public extension services and research
7) Omnipresence of gross yield and absence of economic optimum estimates
8) Concentration on one cultural system at the expense of alternative systems
9) Perception of, and information given about, resistant cultivars
Public regulations
10) Cultivar registration norms
11) More important challenges: food safety, traceability, etc.
Past agricultural policies
12) Payments based on output influenced cultivar choice towards highest-yielding cultivars

3.1. Factors at the farmers' level

3.1.1. Criteria for cultivar choice

The first factor is the direct criteria for cultivar choice by farmers. According to extension services officers, resistance to diseases comes into play only after four other main criteria (gross yield, resistance to lodging (yield security), earliness, and commercial quality) have been considered. A survey among 100 farmers confirmed that the main criteria were yield (main criteria for 64% of farmers) and commercial value (22%), while resistance to diseases ranked only third (14%) (Marot et al., 2005). Extension services officers also reported that the prestige of maximal gross yield remains predominant in farmer-to-farmer contacts, and a glance at the agricultural press confirms that this is indeed a powerful criteria in the whole agricultural sector. Farmers thus generally consider resistant cultivars only if they rank best for yield, which cuts out a number of them.

3.1.2. Incomplete resistance of resistant cultivars

The second factor is the incomplete resistance of resistant cultivars and the unpredictability of the annual prevalence of the various diseases. Few cultivars are completely resistant to disease and degrees of resistance may change from year to year due to agro-meteorological conditions and pathogen evolution. This means that the risk of extensive disease damage is unpredictable, and it exists for almost all cultivars, as complete resistance is rare. As a consequence, the actual benefit of choosing resistant cultivars can only be fully assessed at the end of the season, which is no problem for a scientist, but not very satisfactory for a farmer.

3.1.3. Limited number of cultivars resistant to all frequent diseases

The third factor is the limited number of cultivars that are resistant to all frequent diseases. Few cultivars have a high level of resistance to each of the four most common diseases in the region (FHB, Septoria leaf blight, brown rust and yellow rust). Most cultivars resistant for one disease have at least some susceptibility to one or two of the other diseases, which makes the choice of resistant cultivars harder as all diseases are expected to occur from time to time. In 2004, only 5 out of the list of 24 main cultivars had 'good' (level 4) resistance to all four diseases. Some fungicide applications are thus needed even when resistant cultivars are used.

3.2. Factors at the market level

Private stakeholders influence crop protection practices in three ways: (a) an internal bias in supply companies in favour of fungicide rather than seed sales; (b) a bias towards fungicide applications among supplier salespeople; and (c) the low priority attached to breeding for disease resistance in seed companies.

3.2.1. Internal bias in supply companies in favour of fungicide rather than seed sales

Supply companies have a preponderant role in the cereal sector: these firms sell crop protection products, fertilisers, seeds, advice and agricultural machinery to farmers and also collect their cereal output. In Wallonia, two large organisations share two thirds of this market (one private firm and one farmer cooperative). In each of these two supply companies, the seed department accounts for a very small share of the sales (6–7%). Crop protection products and fertilisers are much more profitable departments. According to a seed-department head, this internal imbalance greatly influences the firms' activities, including the choice of cultivars on which the organisation takes out licences. The contradiction lies in the fact that a seed department should promote the most resistant cultivars, but this is not a priority for the crop-protection and fertiliser departments, which focus on cultivars with the highest yields. Suppliers primarily make money from fungicides and not from seeds. The fact that seeds and crop protection products are sold by the same distribution networks thus has a key influence on the weak development of disease-resistant cultivars.

3.2.2. Bias towards fungicide applications among supplier salespeople

The second factor is also located with supply companies. Local salespeople from the supply companies have the greatest influence on farmers, especially since the network of regional public extension officers has been dismantled. They are the only external technical advisers that have direct and regular contact with every farmer. Salespeople advise farmers on cultivar choice as well as on crop protection products and fertiliser choice. They are partly paid according to sales, which induces a second bias in favour of high-input systems. The highest-yielding cultivars that perform best under high-input conditions are thus promoted even if they are poorly resistant to diseases. Fungicide application is promoted, even in situations in which it is unnecessary. Indeed, a second fungicide treatment is often suggested, even when it is neither necessary nor profitable, as farmers, especially risk-averse farmers, tend to think of fungicides as forms of insurance. This factor was mentioned by public extension officers in interviews, and is also present in their articles in their annual handbook (FUSAG and CRA-W, 2005). Supply companies deny it.

3.2.3. Low priority attached to breeding for disease resistance in seed companies

The third factor relates to breeding companies. The real importance of breeding for resistance is controversial. While resistance is often mentioned as a priority in breeding programmes (Eyal, 1999), some private breeders recognise that resistance is not as important an objective in their work as in that of public breeding institutions. Real progress in resistance improvement takes a long time: public breeding centres have fewer constraints to engaging in this work than private breeders, which have short-term profitability constraints, such as 'put at least one cultivar on the market a year' to remain competitive.

This lack of interest does not mean that modern cultivars have lower resistance levels than old cultivars, but that there has been an under-investment in this breeding objective. During the three last decades, the existence of fungicides and the focus on high-input systems has led to a greater focus on yield than on resistance. As a consequence, breeding for resistance has not been very profitable. The effort put into breeding for resistance to diseases has thus been insufficient, compared to what breeders could now offer, in terms of commercial cultivars, if their main objective had been to produce hardy cultivars. In addition, breeding-for-resistance programmes have focused on vertical resistance rather than horizontal, polygenic, resistance. This strategy is not sustainable as the example of the breakdown of *Yr17* resistance to yellow rust shows (Bayles et al., 2000).

3.3. *Factors at the extension services level*

Public extension services influence cultivar choice and agricultural practices. In Wallonia, public extension work on wheat production is run by the Wallonia Agricultural Research Centre (*Centre de Recherche Agronomique de Wallonie*, CRA-W) in conjunction with the Gembloux Agricultural University (*Facultés Universitaires des Sciences Agronomiques de Gembloux*, FUSAG) and the Faculty of Bioengineering at the Catholic University of Louvain (*Université catholique de Louvain*, UCL).

To study the role of public extension services, we relied both on interviews with stakeholders and the analysis of the contents of the *Livre Blanc* between 2000 and 2005. The great majority of experimental research concerned the influence of one variable – such as sowing date or cultivar choice – on gross yield (46.3%), the phytosanitary contribution to yield (27.3%), cultivar disease-susceptibility estimates (10.2%), and the development of disease in a crop (9.8%) (Table 2).

Three factors that interfered negatively with a wider use of resistant cultivars by farmers were: (a) the omnipresence of gross-yield calculation and the absence of economic-optimum estimates; (b) the perception of resistant cultivars by extension services officers; and (c) the concentration of applied research on one cropping system. The results of interviews and observations of advice given by extension services to farmers in public presentations were consistent in this respect.

Table 2 – Experimental research reported in the *Livre Blanc* between 2000 and 2005

	Number ($n = 205$)	Percentage (%)
Type of result		
Influence of one variable on gross yield (kg/ha)	95	46.3
Phytosanitary contribution to yield (kg/ha)	56	27.3
Cultivar disease-susceptibility estimates (scale of 1 to 4)	21	10.2
Disease development in a crop (% affected area)	20	9.8
Difference in revenue between various cropping systems (expressed in kg/ha)	16	7.8
Mycotoxins estimates (DON or mg/kg)	7	3.4
Type of field tests		
Long term experiment (over 3 years)	37	18.0
Comparison between various cropping systems	35	17.1
Comparison including low-input systems under agri-environmental schemes	20	9.8
Tests on organic fields	2	1.0

3.3.1. *Omnipresence of gross-yield calculation and absence of economic-optimum estimates*

Public extension work, as measured by the content of the *Livre Blanc*, relies systematically on calculations of gross-yield, and pays little attention to estimates of economic optimum. While nearly half of the results of experimental cereal research focused on gross yield (46.3%), only 7.8% employed a more comprehensive economic analysis by including the costs of inputs for cropping systems which made a moderate or intensive use of inputs (fertilisers, fungicides). In the five-year period, only one paper developed a full economic analysis in which units were euros/ha and not kg/ha. Other analyses (28%) attempt to 'translate' costs of inputs such as crop protection products or spraying applications and fuel into 'kg/ha equivalents'.

This is particularly surprising because the results of the few analyses on economic optimum in cereal production gave original and interesting results. Some economic comparisons between high- and low-input cropping systems were carried out in the context of agri-environmental schemes in the early 2000s (Buyze et al., 2003; Dekeyser et al., 2003, Soete et al., 2003). Their conclusions were clear: the quest for the highest gross yield is not the best strategy to maximise net gross margin when wheat prices are low (which was the case at that period). Instead, a choice of disease-resistant cultivars in low-input systems gave the economic optimum when agri-environmental premiums of Common Agricultural Policy (CAP) second pillar were taken into account. Soete et al. (2003) are unequivocal: 'Considering the latest four years of results, the economic optimum was reached by the low-input system complying with agri-environmental schemes. The combination of input reductions and agri-environmental premiums legitimises the 5-year commitment to agri-environmental schemes'.

Paradoxically, this type of result has not been published since 2003. Results of low-input systems were nevertheless confirmed with additional, unpublished results: a few resistant cultivars were even the most profitable in low-input systems without agri-environmental premiums (Dekeyser et al., in press). Results from a French research network on low-input systems showed the economic advantages of such systems in comparable cropping systems (Felix et al., 2005; Rolland et al., 2005). The situation in France is discussed in more detail in Section 4.1 below.

However the published information about these economic comparisons was limited. In the *Livre Blanc* results from these economic comparisons were generally published as short occasional papers on agri-environmental schemes (during the time these schemes had a bad image as farmers had to commit to them for five years to get the premiums). Only once, in 2001, were the results integrated into the general section dealing with the conventional production of wheat. Actually, public extension services consider that supplier salespeople who have direct contact with farmers distribute the most relevant information from the handbook. The place of the information in the handbook would thus not have great importance. However this might not be true for this type of information, as suppliers might minimise the importance of such results because they rely on sales of fungicides and fertilisers and have thus no interest in promoting low-input systems. As one manager put it clearly in an interview: ‘Between ourselves, calculation of gross yield (instead of economic optimum) suits the whole business: the agricultural press, the phytosanitary companies, etc. It leads to greater consumption. Everyone has an interest in it’.

The results of our survey were consistent with these findings. During interviews, the issue of economic optimum was only raised by advocates of resistant cultivars. Public extension officials either dismissed such calculations or discussed the many difficulties in carrying out the calculations. These difficulties comprise the costs of implementation, the fact that the results were less immediately comprehensible than gross yield, the fact that the calculation was more complex as more variables have to be taken into account, and the difficulty of adopting a standard calculation when some farmers take the costs of labour or oil into account and others do not. A few were indifferent to economic-optimum estimates which seemed to them an unimportant measure for farmers, since their variable expenses are low compared to their fixed expenses such as farm rental and loan repayments.

Whether farmers calculate their economic optimum themselves or not is thus considered an open question by scientists and technical advisers in the cereal sector in Wallonia. No surveys of farmers‘ practice in this respect have been carried out in the region. However, most scientists and public extension officers think that farmers, or even agri-managers, do not calculate economic optimums. In any case, it seems rather unlikely that a farmer could, without the appropriate information and tools, analyse the results from 20 to 70 cultivars and compare the results of three different cropping systems (low, moderate and high-input)!

3.3.2. *Perception of resistant cultivars by extension services officers*

According to prominent public extension officers, cultivar susceptibility to a disease is ‘the probability of having to spray at any given time’. A resistant cultivar ‘raises the chances of not having to apply two fungicides and allows greater flexibility in the time of application’ [which is very important for farmers who may be busy with livestock management or other activities at a particular time] ‘without excluding an intervention’ (Couvreur and Herman, 2002). Public extension officers thus promote their own perception of resistant cultivars: while they advise choosing cultivars resistant to the most systematic diseases (Septoria leaf blight and brown rust), they fail to emphasis the economic benefits of resistant cultivars in low-input cropping systems.

3.3.3. *Concentration of applied research on one cropping system*

The third element that we identified as a factor impeding the wide use of the best resistant cultivars is the concentration of experimental research on one cropping system, at the expense of alternative systems. In the *Livre Blanc*, there were six research papers on agri-environmental schemes between 2000 and 2003, but only two one-table two-page papers on organic wheat, one in 2001 and one in 2002. During the entire period, only 10.6% of the research tables presented to farmers concerned agri-environmental schemes, and only 1.1% covered organic wheat. This research was exclusively published in specialised occasional papers. Regular papers on general wheat production only covered research on agri-environmental schemes once in the entire period, and never compared conventional and organic wheat production systems. Occasional papers focusing on agri-environmental schemes formed the vast majority of published research on both the economic optimum (12 out of 14 research tables) and the comparisons between different input levels (21 out of 32 research tables).

Large-scale comparisons between different cropping systems, including organic systems, are indeed extremely rare (Champeil et al., 2004b).

The experimental conditions of cultivar field tests also reflect this concentration on one particular cropping system. Experimental fields are sprayed twice with fungicides to fully protect the plant from disease damage, as the main objective is the assessment of the gross yield potential of cultivars. Other considerations also play a part, such as the desire of farmers who host cultivar field tests to show ‘nice’ fields. Results from the main network of cultivar tests influence not only farmers’ choices but also seed companies’ strategic decisions such as the areas devoted to seed propagation. The decision to double-spray experimental areas (instead of systematically comparing the results with one and two applications) may thus induce farmers to adopt the same strategy, even when it is not the optimal strategy from an economic point of view.

Besides, it was evident in our survey that scientists had a poor knowledge of results from non-experimental research. The stakeholders and scientists we interviewed could hardly cite any local socio-economic research or surveys on farmers’ strategies, decision modes or use of external information. One prominent scientist only knew of two: one in 2004 and another in 1985 (Marot et al., 2005; Duveiller et al., 1985). Studies on the development, advantages and drawbacks of agri-environmental schemes such as low-input wheat systems attracted only limited interest from the agricultural research community. Data on the market share of each commercial cultivar, on cultivar genealogy and heterogeneity, on fungicide application strategies and crop rotation schemes used by farmers was unavailable. However all this information is necessary to assess how improvements in integrated pest management could be achieved. Low commitment to social sciences and non-experimental research in general results in a limited openness to critical research on and analyses of the organisation and activities of the food chain.

When combined, the three elements listed above give a weak signal to farmers that resistant cultivars and alternative cropping systems could be a profitable system. Publications by extension services, and the agricultural press in general, matter. As communication theorist Cohen observed what became a widely accepted fact in communication ‘the press is significantly more than a purveyor of information and opinion. It may not be successful much of the time in telling people what to think, but it is stunningly successful in telling its readers what to think about’ (Cohen, 1963). A systematic calculation of gross yield instead of economic optimum, a focus on high-input systems and a disregard for low-input systems all influence cultivar-choice strategies.

3.4. Factors at the public regulations level

Public regulations also greatly influence agricultural practices. We identified several public norms and regulations that had a direct or indirect influence on farmers' behaviour.

3.4.1. Cultivar registration norms

In Belgium, experimental tests for registration are historically conducted with fertiliser use matching farmers' practices but under no-fungicide conditions. These conditions are thought to positively influence the acceptance of disease-resistant cultivars, as they perform better than susceptible cultivars under these conditions. New cultivars are assessed following a grid of criteria and receive a positive or negative grade for each criterion depending on whether its results are better or worse than the mean for that criterion. This grade is then multiplied by a weight according to importance of each criterion (1 for yield, 0.9 for resistance to lodging, 0.2–0.3 for resistance to each of the four diseases). Grades are finally summed to give a final mark that results in cultivar acceptance if it is positive. The impact on resistant cultivars is thus only moderate: cultivars can compensate for high susceptibility to a disease with a high score for yield. The procedure may dismiss some hardy cultivars: resistant cultivars that perform well under low-input conditions may not outperform higher-yielding cultivars in highly fertilised conditions.

3.4.2. Prevailing challenges in the agri-food chain

Two important challenges, food security and food traceability, conflict with pesticide-reduction efforts and the promotion of integrated pest management. These socio-economic issues, which are not directly related to crop protection, worry all stakeholders a lot more than a reduction in fungicide use and this fact has to be linked with cultivar use. New constraints such as the Integral Management of Food Chain Quality, monitoring contaminants in the food chain, and traceability schemes are the number one problem for all stakeholders. European and Federal public regulations are being implemented or even anticipated at all levels. Our survey showed that this puts a heavy burden on all public and private organisations involving costs, human energy and time. In comparison, a recent Federal programme of pesticide reduction was not even mentioned in any interview, and prominent public stakeholders were not aware of it. Public extension services, civil servants in administration, and scientists involved in applied cereal research have finite time, energy and resources; they use these to deal with the most important current priorities. Food safety and traceability are thus indirectly reducing the attention stakeholders can pay to the importance of cultivar disease resistance or broader pesticide reduction programmes (FHB is an exception here, as we will see below).

3.5. Factors based on past agricultural policies

A number of factors relate to the importance of gross yield and the biases it induces in cultivar and cropping-system choices by farmers. For some time, farmers have received agricultural subsidies based on their output level. As these payments were a major part of farm revenue, this aspect of CAP is largely responsible for the bias towards the high yield. It pushed farmers towards the quest for the highest achievable yield, and influenced both breeding objectives and the evaluation criteria in extension services.

4. Discussion

This case study is limited to a specific crop, a few diseases and a particular region yet our results have a broader significance. Firstly, comparable situations exist in other countries, especially in neighbouring France (Section 4.1). Secondly, our analysis leads us to depict the current cultivar use and crop protection situation in Wallonia as an example of a 'pesticide lock-in' situation (Section 4.2). Thirdly, we discuss the ways of promoting a wider use of multi-resistant cultivars and low-input systems (Section 4.3).

4.1. Comparison with other situations

The existence of factors explaining the weak adoption of disease-resistant cultivars has also been analysed in other agri-food chains in Belgium. Thirteen factors explain the current failure of scab-resistant apple trees to become the main commercial cultivars, despite the fact that they can save up to 70% of the necessary fungicide treatments (Vanloqueren and Baret, 2004a).

The comparison of our results with those in other countries is not straightforward. Few recent analyses of cultivar adoption in Western Europe exist, since research on this topic has been almost completely abandoned in developed countries. It is gaining a new momentum with the growth of genetically modified crops, yet there is currently very little experience of this in Europe, with the exception of maize in Spain.

The use of multi-resistant cultivars may be seen as a component of truly 'integrated' pest management (IPM). However, the IPM adoption literature is also limited, especially in Western Europe. Following Jeger (2000), there has been too little analysis of situations in which constraints to the adoption of alternative pest control strategies have been overcome. IPM is a process that includes a wide array of methods and products: resistant cultivars are only one component of it (Ehler, 2006). The factors leading to the adoption of multi-resistant cultivars are not directly comparable to those involved in the use of treatment thresholds, conservation measures, beetle banks, etc. There are however similarities between the factors we identified and the constraints to IPM adoption in the US identified by Ehler (2006). The first is the presence of conflicts of interest among private technical advisers employed by pesticide companies. The second is the fact that pesticides can be a cheap insurance policy: we mentioned the incomplete resistance and unpredictability of epidemic development as a negative factor in adoption, and these factors are directly linked to risk (and thus to insurance). The third is the current cultural routines of agricultural research scientists. Ehler mentions the resistance of scientists to a true integration of the pest disciplines, while we identified negative factors such as the concentration of research on one cropping system, the way resistant cultivars are assessed, and the omnipresence of gross yield rather than the economic optimum as the main reference point.

The comparison of our analysis with the situation in France is most relevant. France borders Wallonia, and faces a comparable situation as far as resistant cultivars and low-input systems are concerned. According to official surveys among farmers, multi-resistant hardy cultivars represented less than 3% of French wheat area in 1999 (INRA, 2001), but this had increased to 16% by 2004 (Rolland et al., 2005). The French definition of hardy cultivars fits within the context of low-input systems: it includes productiveness and multiple disease resistance, but allows susceptibility to one disease, such as FHB (Rolland, personal communication). Such cultivars were studied in France in a large network of field tests between 1999 and 2002 (Meynard et al., 2003), which were further extended in 2003–2005. The results from this programme were published in the agricultural press, which is also available in Belgium (Felix et al., 2005), as well as in scientific communications (Rolland et al., 2002, 2003; 2005; Loyce et al., 2006). The 2003–2005 programme concluded that in 45 out of 66 locations, the combination 'hardy cultivar-low-input system' gave the highest economic margin.

Hardy wheat cultivars are presented as a success story of public agricultural research. However, the historical analysis of contemporary plant science research in France by Bonneuil and Thomas (in press) demonstrates that the development of hardy cultivars depended solely upon the persistence of a few scientists who swam against the flow until the late 1990s, when wheat prices had fallen and agricultural professionals start to look at their results differently. The main factors counting against disease-resistant cultivars in France were similar to those discussed in the Belgian situation. Impediments run from the strong political wish within research institutions to invest in hybrid wheat and plant biotechnologies rather than in traditional plant breeding for hardy cultivars, to the unwillingness of public technical institutes – which run the main agricultural journals – to publish the results of field-test research and economic-optimum analysis of hardy cultivars in low-input systems. The negative role of farmer cooperatives which are input suppliers, and of extension services, has also been mentioned as a factor working against the development of hardy wheat cultivars (Meynard and Savini, 2003).

The role of French private breeders in the development of hardy cultivars is controversial among scientists and stakeholders in the cereal sector. While a few breeders have been involved for decades in the development of hardy cultivars, and have produced sufficient cultivars to fit all needs today, it is argued that the main farmer cooperatives and breeders (some of which are partly owned by agro-chemical companies) have long promoted cultivars best adapted to high-input systems. The cultivar registration norms have been a constant bone of contention and site of power struggles between promoters of hardy cultivars and promoters of high-input systems (Bonneuil and Thomas, in press). Concentrating plant breeders' efforts on horizontal, polygenic resistance is a more sustainable strategy than focusing on vertical resistance, but not all breeders have yet made the transition.

4.2. *Pesticide lock-in*

Lock-in and associated path-dependence concepts have been suggested to explain the stability of socio-technical systems, particularly the sensitivity of competing technologies on initial conditions when increasing returns occur (David and Arthur, 1985; Arthur, 1989). One technology may become dominant over others that perform similar functions and compete for adoption by economic agents, even though it has inferior long-run potential. This 'path dependant' process is self-reinforcing and may lead to a technological 'lock-in' situation in which the dominant technology excludes competing and possibly superior technologies (Liebowitz and Margolis, 1995).

The existence of path dependence and lock-in processes has been shown in the realm of agriculture (Cowan and Gunby, 1996) even though most of the path dependence literature focuses on technological change in industry. Lock-in situations have been observed in several agricultural situations and food chains, such as for the use of pesticides in cotton and cereals (Cowan and Gunby, 1996; Wilson and Tisdell, 2001), in animal breeding (Tisdell, 2003), and in specific cases of animal breeds or plant cultivars having a tremendous influence on their sector (examples in Belgium include the Bintje potato cultivar, the Belgian Blue Beef and the Holstein breeds (Stassart and Jamar, 2005)). The factors we identified in our study are comparable to the factors Cowan and Gunby (1996) found to be impediments to a switch from the historical use of chemical pesticides to integrated pest management (IPM) strategies: uncertainty, coordination problems, technology immaturity, inflexibility, technology inertia and path-dependence. If the presence of a few negative factors is not a barrier in itself, the build-up of numerous negative factors creates a lock-in situation.

In the course of the twentieth century, chemical pesticides gradually became the main pest control strategy. Modern wheat cropping systems are now 'locked-in' to a fungicide-dependency situation, even though the global situation (wheat prices, crop protection costs, cultivar characteristics, alternative crop protection strategies, available scientific knowledge) has changed. It has been shown that 'escaping lock-in' requires exogenous forces. Unruh (2002) analysed this situation for escaping our economy's dependence on fossil fuels. In the agricultural field, it has been shown that modifying practices in apple orchards demanded special efforts and conditions in the entire agri-food chain (Collet and Mormont, 2003; Vanloqueren and Baret, 2004b). Accepting that apples are very different from wheat, the same is probably true for the wheat sector.

Not all lock-in situations are completely locked. New conditions (such as tougher pesticide regulations, changes in cereal prices, changing consumer preferences, programmes of pesticide reduction, etc.) may 'dismantle' the lock-in. Even if we depict the situation as a lock-in, another observer may see only slow change. It depends on a qualitative assessment of the situation. However, naming the lock-in helps us understand that specific actions must be undertaken to get out of this static or very slowly changing situation.

4.3. *The transition to sustainability: paths to a broader use of multi-resistant cultivars and low-input systems*

An agricultural system can be locked-in to past solutions and get blocked from current optimal configurations. This situation is dependent upon past paths taken by farmers, extension services, agricultural policies and agricultural research systems. If the society as a whole considers this situation sub-optimal, scientists and the public authorities have a role to play in contributing to the transition to a more sustainable system.

As far as scientists are concerned, the phasing out of input intensification in wheat cropping systems induces a need for both long-term and large-range experimental studies, a neglected research area within agronomy (Meynard et al., 2003; Meynard and Savini, 2003). It also requires multidisciplinary research. There are various opportunities for public authorities to escape the self-reinforcing and path-dependant trend of input intensification. Obstacles to the use of resistant cultivars can be removed to accelerate their adoption. This can be a part of broader plans to accomplish pesticide-reduction programmes. A general switch to a systematic use of multi-resistant cultivars in the context of integrated pest management will certainly need more of a driver than the gradual adaptation of farmer strategies to cereal prices, as neoclassical economic theory assumes will be sufficient.

It is interesting to focus on two very different diseases. The case of FHB and associated mycotoxins is illustrative of how public authorities can still have an impact on food chain activities within globalised and free agricultural commodity markets. The prospect of a new European directive on mycotoxins led the whole cereal sector to anticipate it at all levels. Market stakeholders introduced maximal levels of mycotoxins in wheat even in the absence of binding rules. A few specialised food chains created a list of recommended cultivars while breeding programmes, private and public, integrated new sources of resistance to FHB. Research institutions launched specific task forces and research programmes such as risk forecast models or low-cost mycotoxins detection toolkits. These efforts were coordinated on the European scale for a chain-wide strategy (Scholten et al., 2002). However pesticide reduction efforts are only weakly coordinated in Wallonia and in France. Other countries, such as Denmark, have achieved great success with long-term pesticide reduction efforts.

The first channel through which public authorities may act is norms for cultivar registration. In a number of countries, minimal levels of cultivar resistance to FHB have been introduced as part of broader plans to control the risk of contamination of food chains by mycotoxins (Ruckenbauer et al., 2004; Snijders, 2004). Minimal levels of resistance to each of the most frequent diseases would be a strong incentive for breeders to invest more resources in breeding for disease resistance. Likewise, the registration procedure might include an ex-post assessment after a two- or three-year period: cultivars that lost resistance over time due to pathogen adaptation could be removed from the market or charged extra for registration maintenance.

Registration procedures should also be adapted to fit with low-input cropping systems (low fungicide and low fertiliser use) by testing cultivars in such conditions in order to promote hardy cultivars. These institutional innovations would have to be adopted on a European scale to have any real impact.

Secondly, extension services should be adapted to new socio-economic and societal trends. Public action must induce a paradigm shift to overcome strongly rooted socio-economic trends. Productivism (Walford, 2003), illustrated here by the prestige of maximum gross yield, must be replaced by objectives such as economic and environmental efficiency. Extension publications thus have to be remodelled; the single fact that they presently focus on yield, and not economic optimum, has great importance. As price conditions vary annually and cultivar turnover is high, research and extension should focus on answering a currently unasked question: 'Is the systematic choice of the best multi-resistant cultivars – and of low-input systems – the most profitable choice for farmers on a 3-, 5- or 10-year perspective?' Cultivar choice software may become a useful tool for cultivar choice (Barbottin et al., 2006). Economic and environmental optimum estimates could be made for all cultivars in cropping systems with varying levels of inputs (fertilisers, fungicides and straw shorteners) and for different wheat-price scenarios. More comprehensive information about the advantages of resistant cultivars could also be diffused.

Thirdly, the promotion of hardy multi-resistant cultivars should ideally go hand-in-hand with efforts to promote wheat production systems less prone to fungal diseases. Various non-breeding strategies, such as spatio-temporal alternation or cultivar mixtures, can improve the durability of the genetic control of pathogen populations (Mundt, 2002, Cox et al., 2004, Vallavieille-Pope, 2004). It has been shown that these strategies receive insufficient attention in agricultural research systems (Vanloqueren and Baret, submitted for publication). Both research and development, and agricultural policies should take these strategies fully into account and promote them (Diamand, 2003).

Besides using 'positive' methods to promote these preventive strategies, public authorities can also use 'negative' methods to reduce the use of pesticides. Tighter pesticide regulations and a dissuasive tax on pesticide use are two of the main tools that have been used by countries, such as Denmark, which have implemented national pesticide—use reduction plans sooner than Belgium and France (Aubertot et al., 2005).

5. Conclusion

The failure of disease-resistant wheat cultivars to become a mainstream cultivar choice in wheat production is not due to poor technical characteristics such as low yield or poor bread-making quality. Factors impeding the development of resistant cultivars exist at all levels of the food chain, from farmers to input suppliers to CAP policies. Even extension services do not fully support the use of disease-resistant cultivars in low-input systems, despite their recent economic successes. This paper has shown that modern wheat systems are in a locked-in situation favouring the use of high inputs (fertilisers, chemical pesticides and straw shorteners). The development of hardy multi-resistant cultivars and profitable low-input systems will require not only improved cultivars but also planned efforts.

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