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par

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Essai sur les conséquences environnementales de la recherche et développement sur les variétés agricoles

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Composition du Jury :

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ÉCOLE DOCTORALE
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Titre : Essai sur les conséquences environnementales de la recherche et développement sur les variétés agricoles

Mots clefs : variétés agricoles ; recherche et développement ; protection de la propriété intellectuelle ; externalités ; environnement ; course à l'innovation ; optimum social

Résumé : La forte hausse des rendements agricoles, observée tout au long des 150 dernières années, est, pour une large part, due à l'amélioration des variétés, résultant elle-même essentiellement de processus de recherche et développement. L'optimalité sociale de l'effort de recherche entrepris par les firmes de ce secteur, ainsi que des institutions encadrant l'activité de recherche, constituent un sujet important pour les politiques publiques. L'objet de cette thèse est de contribuer à éclairer cette question, en s'efforçant de tenir compte de l'impact sur l'environnement de l'innovation en matière de variétés agricoles. Nous examinons ce sujet à travers trois prismes différents : celui de l'innovation en tant que telle, celui du processus de recherche, et celui du cadre institutionnel offert aux entreprises de recherche. Nous montrons que la prise en compte des effets environnementaux de la recherche en modifie les optima, et devrait donc conduire à une adaptation du cadre incitatif et règlementaire.

Title : Essay on the environmental impacts of research and development on plant varieties

Keywords : plant varieties ; research and development ; intellectual property protection ; externalities ; environment ; patent race ; social optimum

Abstract : The sharp increase in agricultural yields in the past 150 years owes a lot to the improvement of plant varieties, which, to large extent, is the result of the research and development process. Whether the research and development effort undertaken by firms operating in this sector and institutions regulating research are socially optimal is an important question for public policies. This thesis aims to contribute to tackling this issue, and its main contribution is to endeavor to account for the impact of crop innovation on the environment. We address the question through three different perspectives : innovation *per se*, the research and development process, and the institutional framework available to research firms. We show that environmental externalities of research significantly modify social optima.

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Contents

General introduction

In his *Essay on the Principle of Population as it Affects the Future Improvement of Society, with Remarks on the Speculations of Mr. Godwin*, Thomas Malthus pointed out that *the lack of available land* for agricultural production would lead to food shortage by the middle of the 19th century. This would impose the stagnation of world population. To some extent, Malthus was probably right: keeping constant the agricultural yields he could observe in the late 18th century, more than total land available on Earth would have been necessary to meet the needs of an increasing population. However, the yields of plants, whatever the crop and in almost all regions in the world, sharply increased during the 19th and, even more strikingly, the 20th century (Beddow et al., 2009). Hence, Malthus's previsions did not materialize, and agricultural output increased quite steadily throughout the 19th and the 20th centuries, which, in turn, allowed world population to increase.

Although hunger remains a major issue for global development, total current agricultural production would be sufficient, if shared better, to meet global needs (Godfray et al., 2010). There would be various options to do so, among which reducing waste of agricultural output (Hodges et al., 2011), or changing diets into less demanding ones (Meier and Christen, 2013) are certainly the most promising ones. Although, in addition, such better sharing of output would be the most eco-friendly approach to tackle hunger, it would require dramatic changes in social behaviors. Furthermore, it should be supported by a strong political will, that may prove difficult to occur, at least on short term. It is thus likely that it will be a part of the solution only. The remainder is most likely to be devoted to an increase in total output, despite constrained arable surfaces (Borlaug, 2002; Tilman et al., 2011). It is acknowledged that agriculture would be able to meet the global demand for food by 2050, but this will be conditional on increases in yields (Waggoner, 1996). Innovation, in every component of agricultural production (plant varieties, machinery, chemicals, etc.), allowed by research and development efforts from both public and private entities, has been at the core of the development of yields (Wright and Pardey, 2002). Future increases in yield will thus most probably depend on further innovations.

Governments have long played a very important role in agricultural productions throughout the world. Public intervention in the agricultural productive system itself has been very common, significantly more than in other activities. The scope of such intervention has been broad, from weak market incentives to direct, fully centralized planification, such as what has been implemented for most of the Soviet Union existence. Nowadays, the implementation of strong incentives is more frequent, such as those (*e.g.* quotas, direct and indirect aids, or exportation support) provided in Europe by the common agricultural policy (CAP). This policy is aimed at ensuring food security, decent revenue for farmers and several other non commercial purposes such as environmental protection (Bureau, 2007). Regulation in the agricultural sector is important, and often goes beyond ensuring a sufficient production or regulating farmers' profits. For instance, in most countries, regulations sets a finite list of varieties that can be cultivated (*e.g.* in the European, only plant varieties registered in the "Plant Variety Database" can be cultivated and marketed). Public regulation of international trade of agricultural commodity is frequent as well. It may include, for instance, exports restriction, like those adopted in 2007/2008 in Russia and Ukraine (Götz et al., 2013).

Several reasons may have justified such a strong intervention of government in agriculture, either from a political or from an economic point of view. The most obvious political reason is probably that agriculture is one of the few really vital production for human life. This encourages governments to keep a strong control over it, especially when they are distrustful of market mechanisms. The importance (or publicly perceived importance) of the agricultural sector as a provider of employment, and the variety and consequences of the risks farmers face (climatic, with a strong dependance of output to weather, economic, with a strong volatility of prices, etc.), also bear responsibility in this vision that agriculture is an economic sector appart from others. Such a specific sector thus deserves more public attention and intervention than others (Bureau, 2007).

In the present dissertation, we will focus on a particular role of such action, namely the public policies of agricultural research and development (R&D) and the way they may correct some market imperfections. It may not be the most obvious and straightforward lever for public intervention in agricultural production. However, the public intervention in agricultural R&D is easily legitimated by economic theory - which complements the political justifications of agricultural policies in general, as explained in the previous paragraph. In presence of imperfections, market equilibrium is likely not to match social optimum (Varian, 1992). This is particularly the case for agricultural R&D. Even more than innovations on any other kind of product, the agricultural ones gather the characteristics of public good. Indeed, except in some cases, once a new variety has been distributed by its inventor, it can easily and almost costlessly be reproduced, violating the rivalry and excludability conditions that define a private good. In the absence of relevant institutions, this leads to a sub-optimal provision, from a benevolent social planner's point of view, of R&D by the private sector. Because, especially for the past decades, agricultural research has been characterized by important sunk costs, the concentration of a few actors sharing most of the market has been a natural outcome (Fuglie et al., 2011). Without public intervention, the concentration of the innovation market, and the market power it confers to its few actors, are quite likely to lead to a slower pace of innovation than socially desirable (Loury, 1979). The role of spillovers of R&D, *i.e.* the positive influence one research firms has on other firms operating in the same sector has long been studied the industrial economics literature, as a major externality of the research process (Griliches, 1991). However, the environmental impacts of the R&D process on agricultural varieties, another category of externalities, have received much less interest by the academic literature in economics.

Several analyses, either in economics or in ecology, have focused on specific consequences of newly developed crops on the environment. A large share of them has considered mainly genetically modified (GM) crops, that have been one of the major innovation commercialized for the past three decades. Most works have concentrated on examining a particular dimension of the environmental impacts of new crops. For instance, various papers have studied the impact of GM varieties on the use of chemicals, particularly on pesticides and herbicides (Qaim, 2009; National Research Council, 2010). Others have studied greenhouse gas emissions (Tubiello et al., 2014), or gene flows and contamination by invasive species (Lutman and Berry, 2006). However, works accounting for the environmental externalities in the economic studies of invention of varieties are still rather scarce. Several fields have been investigated by the economic literature about innovation on varieties. One of the most important and oldest one is the empirical valuation of innovation (Griliches, 1958; Evenson, 2001). Another field of investigation has been the optimal design of intellectual, property protection over varieties, and its consequences on R&D efforts of plant breeders (Yerokhin and Moschini, 2008; Kolady and Lesser, 2009; Thomson, 2014; Lence et al., 2016). Accounting for environmental impacts is likely to change the results of this literature. Whenever environmental externalities of crops innovations are positive, studies that do not take them into account underestimate their social value, and conclude to intellectual property protection (IPP) designs that do not sufficiently encourage innovation. If environmental externalities prove to be negative, of course, the opposite holds.

1 Objectives

In the present thesis, we aim to study how the environmental externalities of innovation on varieties should be taken into account, in the design of related public policies. Of course, examining any dimension of this question would be too ambitious as an objective, and we will have to restrict to some aspects of it.

A focus has to be performed, first, on the concepts used in this work, to clarify them and define their boundaries as accurately as possible. First, we shall define what innovation on crops is or, more precisely, what innovations on crops are. Indeed, *a priori*, considering innovation as a unique and integrated concept is likely to be a strong assumption, that should thus be questioned. Second, before adopting an economic point of view on the externalities of R&D on crops, these should be, at least, briefly surveyed. They adopt many different forms, in particular because many of them are indirect: except for externalities on other research firms, research *per se* does not bring any direct externality, especially on the environment. Only its outcome, *i.e.* the newly developed plant, does. It is thus necessary to identify the channels through which crops innovation has environmental consequences. Our first objective is to provide sufficiently clear definitions and boundaries of these concepts, in order to lead a proper discussion on the environmental impacts of research and innovation on plant varieties.

The private sector has been playing a major role in crops innovation for the last seventy year, especially since the late 1980s. The increasing importance of the private sector has deeply transformed the sector of research on crops. This movement is likely to have changed the impact of research on the environment, or, at least, makes it legitimate to wonder whether it has been the case. The emergence of the private sector has had various causes, and various consequences on the R&D process. It has been made possible by the development and adaptation of relevant institutions, such as intellectual property (IP) rights, and by the prospects of large appropriable returns thanks to enhanced technologies (hybrid varieties, for instance). The structure of the private sector markets have also evolved considerably since the first intervention of firms in research activities. Such evolution raises many questions. Are the IP systems applicable to innovation on plants optimally designed, or is there room to improve them? How does the structure of markets, and in particular the competition in the innovation sector, influence the research effort undertaken by the private firms? These questions have been tackled by a wide range of literature, but, to our knowledge, this literature has not accounted for the environmental externalities of the innovation process, particularly in the case of innovation on plant varieties. In this dissertation, we intend to fill some parts of this gap.

2 Material and methods

In order to provide elements of answer to these questions, the present dissertation falls into three parts, each of them examining a different stage of the innovation process.

In the first part of this dissertation, we focus on innovation *per se*, which is the outcome and the essence of the R&D process. In the first chapter, we provide a general and introductory review of the dynamics in the sector of innovations on the agricultural varieties. In particular, based on the literature on the history of the agricultural sector, and works on this sector in industrial economics, we aim to present its relevant actors and markets, and the new varieties that have been developed recently. More specifically, we shall examine whether and how the relative and absolute importance of some actors has evolved in the past century (private and public sector, research firms and seed producers, etc.). We also summarize the recent evolution in the structure of the market for private actors. Finally, in this chapter, we try to evaluate the overall impact of crops innovations on the environment, by reviewing the relevant literature in economics, ecology and agricultural science.

The second chapter tackles a particular aspect of these consequences of innovation on the environment. It aims to study whether innovation may allow to share land with, or spare land for nature in general, and biodiversity conservation in particular (Green et al., 2005; Fischer et al., 2008). Many authors have acknowledged the crucial role of innovation for sparing some land for nature (Waggoner, 1995). However, more productive crops do not always allow to empirically observe a reduction in cultivated land (Matson and Vitousek, 2006; Hertel, 2012; Villoria et al., 2014). Moreover, to our knowledge, little is known about the impact of innovation on the use of land and the intensity of cultivation simultaneously. It is then rather straightforward to wonder whether, when it does not allow to spare land, innovation may allow to share land with biodiversity. To tackle this question, we extend the model developed by Hertel (2012). In his original work, Hertel focused on land sparing only, and studied whether (and in which circumstances) innovation on varieties is likely to reduce total cultivated land. We complement this approach, using a further development of his theoretical model, in order to study the impact of innovation on both land and chemicals use. This allows to examine the conditions under which innovation may, without policy intervention, yield land sparing and/or land sharing. More specifically, we focus on the impacts of GM crops, drawing a distinction between the three main types of varieties that have been developed to date: herbicide tolerant, insect resistant, and drought tolerant ones.

The second part of this thesis studies the premises of the R&D process, since it is dedicated to the institutions that encourage innovation in general, and innovation on agricultural varieties in particular. It will especially focus on the intellectual protection regimes that promote innovation, and on the social value of innovation. In chapter 3, we review the institutional framework that is available to innovators on plant varieties. In particular, we aim to show that the difference between the existing regimes of intellectual property protection tends to become more and more limited. To study the evolution of the intellectual property regime applicable to crops innovation, we mainly use law sources. We will lean on the contents of existing national laws and international treaties, and of case-law as ruled by national and international courts, as well as on some academic law literature. We also take advantage of the industrial and agricultural economics literatures, to review and discuss the influence of the existing institutional framework of IPP on the invention market, actors and processes.

The fourth chapter discusses the social value of innovation - which legitimates the implementation of intellectual property protection regimes, politically and economically. This chapter is based on a literature review of both theoretical and empirical studies that evaluated the social return of both public and private investment in agricultural research. This review harnesses papers that have relied on the notion of social surplus, following and improving the approach first developed by Griliches (1958).

In the third part we will study the last stage, oriented by institutions to give birth to innovation, namely the research process. In particular, we consider the way research firms interact with each other, in the specific case of innovation on crops. In the fifth chapter, we focus on the competition between R&D firms before the innovation is discovered, and on the description of the strategic behaviors among them. We also review the economic consequences of the design of intellectual property regimes, and finally study the dynamics of innovation in the sector of innovation on agricultural varieties. In order to do so, we first present in details a model of race for innovation, developed by Loury (1979) and Lee and Wilde (1980). This model has been at the core of many subsequent studies of competition in research and optimal legal framework, and we review various theoretical works that build on different adaptations of it. Each of them either discusses a feature of existing IP regimes, or suggests some improvements. [1] Then, we review the application of innovation race models to the specific features of the sector of innovation on plant varieties. In particular, these models account for adaptation of nature and pests to new varieties, as well as different regimes of intellectual property protection available for plant inventions. In particular, the models by Goeschl and Swanson (2003) or Yerokhin and Moschini (2008), reviewed in that chapter, treat the question of social optimality of the R&D effort undertaken by private firms working on plant varieties.

To our knowledge, no academic literature has studied the social efficiency of private firms competing for innovation on varieties accounting for the environmental impact of such innovation. We thus construct a model of patent race that tackles this

[1] These improvements should, in particular, encourage subsequent innovation without decreasing too much the protection of the current holders of IP rights - and, thus, without dampening incentives to innovate too much.

question, presented in chapter six. It is based on the model of Loury (1979) and Lee and Wilde (1980), extended to account for the possibility of several innovations and nature adaptation to innovation. In our model, either one firm holds a monopoly over the right to innovate, or two firms compete against each other in a race for innovation. Whatever the market structure, firms compete against nature as well, to compensate for adaptation of pests. We compare the market equilibrium, in which firms do not take environmental externalities of research into account, with a social optimal in which the social planner does so.

3 Results

From the review we lead in our first part, we may derive several facts and trends. The first trend is related to the respective roles dedicated to aggregated public and private sectors in research on crops. While the development of new varieties has been achieved by the public sector for more than a century until the 1950s, the relative importance of the private sector has progressively increased since then, at least in developed countries. With the introduction of biotechnologies in agriculture, private firms have overcome publicly funded entities in their effort in R&D on varieties (Alston et al., 2010). This justifies a focus on the impacts of privately conducted research. The second observable trend is a strong and recent movement of concentration in the private R&D sector. This has particularly been the case for the last 30 years, with many firms merging with each other, or being acquired by larger conglomerates (Fernandez-Cornejo, 2004). The third relevant fact is the heterogeneity of innovation. Innovation developed throughout the 20$^{\text{th}}$ century is not integrated and uniform but, on the contrary, has taken several shapes: GM or conventional varieties, Hicks-neutral or biased towards a particular input, etc. The effect of innovation on the environment proves to be heterogenous as well, and it is difficult to say definitely whether it has been positive or negative. Indeed, innovation influences the environment through various channels, positively through some of them and negatively through others. Hence, whether the overall effect is positive or negative actually depends on the preferences of the social planner, *i.e.* the weight granted to the different dimensions of environment impacted by crops innovation. After investigating further the impact of innovation in the *land sharing/land sparing* debate, we show that innovation may have various consequences on land and chemical use by agricultural production. The actual effect of innovation depends, first, on the type of innovation considered. More precisely, it is linked to the input factor that is made more efficient by the innovation. It also depends heavily on the price-elasticity of demand, and the production factors' elasticity of substitution. Innovation may simultaneously reduce land use and increase agricultural intensity only if it is biased towards one of these production factors.

The second part of the dissertation reviews the existing institutional framework in which research firms operate, focusing in particular on the IP regime. In chapter 3, we analyze the intellectual protection offered to innovation on plant varieties, adopting a dynamic perspective and looking for recent evolutions in both law and case-law. We present *full patents*, and *plant variety protections* (or *plant certificates*), the two main forms of IPP available around the world (though only one of them may be available in some countries). We aim to present briefly the specificities of each system.[2] This review shows that, rather than being antagonist, these two systems complement each other. Moreover, we show that these regimes, that have been designed, at first, with different objectives and in different contexts, are clearly marked by a movement of convergence in the protections they offer to plant breeders. We provide a special focus on the US, where this movement begun in the early 2000s. We also review, in that chapter, the literature that studies the consequences on the orientation of the corresponding R&D of the existing IPP over innovation on crops. A striking result of empirical valuations of innovation on varieties is the very high social profitability of R&D on crops. Indeed, the social internal rate of return (IRR) exceeded 20% in almost all studies reviewed in chapter 4. Beyond the justification for IPP they provide, such high IRRs raise a question: why don't they lead to more investment in agricultural R&D? We thus suggest a series of explanations to why such figures have been observed, without seeing the deeper implication of the private R&D sector that would seem to have been a rational response. Beyond insufficient incentives, imperfect information and risk aversion may explain a lower investment than what should be observed from rational agents. In addition, these IRR may be overestimated by selection bias, or by methodological issues in cost evaluation.

The third part of this dissertation studies the R&D effort undertaken by private firms and, in particular, questions whether such effort is socially optimal. First, we review models of innovation race. Before an innovation is actually discovered, the

[2] In a very summarized manner, full patent offers a stronger protection than plant certificates.

R&D process is generally an intense competition among research firms. The model of Loury (1979) and Lee and Wilde (1980) we present has been developed in a general framework that is not specific to agricultural innovation. This model is reviewed in detail, since it will be useful when we subsequently review the literature on the characteristics of intellectual protection, and when we build our own model of innovation race. Second, we conduct a review to illustrate the balance that optimal intellectual protection should find between incentive to innovate, brought by long and broad protection, and the associated inefficient market power provided to the holder of IPP. We start by pointing to works that studied the major characteristics of IP, and then turn to the role played by IP regimes in the dynamics of innovation. We finish by examining some suggestions from the literature to enhance existing regimes with more original features. This literature questions the optimality of patents design. It suggests some improvements that may, in particular, encourage subsequent innovation without decreasing too much the protection of the existing patentees - and, thus, without dampening too much the incentives to innovate. Third, we review and discuss some recent theoretical contributions that have adapted the model of innovation race to the particular framework of plant varieties improvements. Indeed, plant inventions face a specific cause of obsolescence (shared with pharmaceutical biotechnology innovations as well) which is the adaptation to innovation developed by nature, and by pests in particular. This phenomenon questions the conclusions of existing models on optimality of R&D effort of private firms. In addition, it sheds an interesting light on the different types of IP, patents and plant certificates, that are presented further *infra*. Adaptation makes patents over plants hardly socially optimal (Goeschl and Swanson, 2003), and justifies the complementary coexistence of patents and plant certificates (Yerokhin and Moschini, 2008). However, these papers do not account for the environmental externalities of research on plant varieties, that is likely to change the socially optimal effort. In order to overcome this limit, in chapter 6, we build a model that shows that when nature adapts either slowly or very rapidly, the private sector tends to overinvest in research. Hence, the incentives for research should be low to mitigate private research dynamism. On the contrary, when nature adapts at an average rate, the private sector tends to underinvest, and, thus, incentives for research should be increased.

Part I

Agricultural innovation, outcome of the R&D process

Chapter 1

A century of transformations of agricultural production

Introduction

The 20th century saw the fastest, and probably deepest, transformations of the agricultural production system since its origins. Every aspect of agricultural production has been impacted. Total output increased at an average annual rate of 2.2% between 1960 and 2013 (FAO, 2016). One of the most striking features of agriculture throughout the 20th century, that played a crucial role in the increase in total agricultural production (Wright and Pardey, 2002) is the large increase in yields. Average yields of rice and maize, for instance, increased from roughly 1000Lb/acre in 1900 to around 8000Lb/acre in 2005 (Beddow et al., 2009). Such increase owes a lot to mechanical (the light tractor has been invented in the 1920s), chemical (widespread use of fertilizers started in the 1930s) and biological (corn hybrids have been first produced and supplied to farmers in 1926) innovations, mainly thanks to both public (especially in the first half of the 20th century) and private (from the 1980s on) R&D (Fernandez-Cornejo, 2004). Mechanization, wide adoption of fertilizers, herbicides, pesticides and new varieties also transformed deeply the role of farmers, their social and working conditions, the size of farms, etc. Research and development has played a major role in this revolution of agriculture, and biological innovation has been a major outcome of the research process and contributor to changes in the agricultural production process. With the increase in agricultural output, the extension of cultivated land and the changes in input mix - in particular the diffusion of chemicals use -, the environmental footprint of agriculture has also changed dramatically.

Agricultural R&D used to be a rather informal activity in the 19^{th} century. It became a more formal and publicly supported sector in the early 20^{th}, and has then turned into a highly profitable and dynamic, mainly privately run one in the 1980s. Such evolution has been a central determinant of the changes in the agricultural system, and notably its environmental impact. The characteristics of innovation on varieties, of which genetically modified organisms (GMOs) is a major component, and the way new crops produced and commercialized in a concentrated sector, determine future discoveries and thus future orientations of production. Agriculture has environmental externalities via various, interlinked channels, such as chemical spread, land use and development pest resistance, and the impact on the environment of R&D on varieties thus flows through each of them.

1 From crops picking to pharming: a brief history of varieties R&D in the 20^{th} century

The need for innovation in the agricultural system has been driven by several factors. Innovation has been an answer to the limits highlighted by Malthus, that allowed the global population to increase from two billions humans in 1900 to more than 6 billions in 2000. Meeting the needs of the growing global population, simultaneously with new industrial and non-food uses of agricultural production (biofuels, for instance), subject to the constraint of limited surfaces dedicated to agricultural production made a sharp increase in yields necessary. As in other sectors, the prospects of social welfare and, with the development of relevant institutions, private profits have also triggered innovation. R&D in general, and on varieties in particular, can be, and has been, entrusted to various actors. In the early days of agriculture, crops innovation was mainly allotted to farmers themselves, who picked up wild varieties and selected some offsprings of their cultures, because they presented characteristics adapted to the specific conditions of their own fields. Farmers also developed their own best practices in cultivating land. Then, because the innovation needed to push forward the technological frontier required larger investments in material and human capital, on a longer term, individual farmer ceased to be the relevant scale. Either public sector or R&D firms had to pick up the burden of innovation, which happened in the late 19th and early 20th century. By that time, it had been acknowledged that market failures (in particular, the lack of appropriability of research benefits, cf *infra*) made the public sector the most relevant actor for conducting research on varieties. After technological (with the development of hybrids), and then institutional (with the implementation of intellectual property regimes) changes solved these market failures, private firms entered the innovation race (Pardey et al., 2014).

1.1 The publicly-funded development of selected and cross-bred traditional varieties, and the emergence of the private sector

From the origins of agriculture to the late 19th century, improvements in agricultural productivity have been mostly driven by informal selection of varieties. Farmers "tinkering" (selecting traits among their cultures, picking up and crossing wild varieties, etc.), or plant prospectors importing improved crops from abroad have been responsible for "great advances in American agricultural productivity, [...] before the modern scientific age" (Alston et al., 2010, Chap. 7). As claimed by Pardey et al. (2014), the beginning of scientific breeding of plant varieties can be dated back to the end of the 19th century, when Gregor Mendel's works on heredity in plant reproduction were discovered again.[1] This re-discovery has triggered the adoption of a scientific approach in selection and reproduction of plants, allowing breeders to isolate and maintain specific traits through generations of plants. Such activity has been essentially undertaken by publicly funded institutions, at least until the 1930s. Alotting research on plants to the public sector was largely justified by several market imperfections. In particular, in the absence of proper institutions, agricultural innovation gathers the characteristic of public goods. Indeed, improved plant varieties are, first, non-rival. The costs of collecting a few seeds or plant parts from existing cultivations of improved varieties is almost negligible. Innovation on

[1]In the middle of the 19th century, Gregor Mendel studied specific traits in garden peas. In particular, he focussed on how these traits were transmitted from a generation to the subsequent ones (Fernandez-Cornejo, 2004). He published his theory in 1866, but his results remained unused for 35 years.

plants, second, is non-excludable as well. Especially in the early 20^{th} century, breeders could hardly trace their seeds and prevent a farmer from replanting, or giving away, the product of its cultivation. Thus, agricultural innovation is under-provided by a market of private actors and requires public intervention.

The reasons why agricultural innovation is a public good can be summarized as a lack of *appropriability* of the R&D outcome. Appropriability over plants is weak in general, but is heterogenous across plants, depending strongly on the way they propagate:

- Asexual reproduction involves one single plant, which, hence, clones itself (rather that *reproduces* in the common sense of this term). It may occur from either vegetative reproduction (in that case a whole new plant can arise from a piece of an existing plant) or from *apomixis* (the new plant germinates from a seed or a bulb produced by the plant itself and that does not requires any fertilization). Potatoes or oignons are examples of asexually reproduced plants. This type of plant is very stable through successive generations. It is thus obviously quite difficult for the breeder of an asexually reproduced plant to prevent farmers from replicating its invented variety (as long as they have access to one specimen of the plant), and hence to appropriate the benefit of its invention.

- Sexual reproduction requires the fertilization of an embryo (*i.e.* the gathering of a male gamete, the pollen, with a female gamete - be it pistil, cone, etc.) for propagation, which relies on the production of seeds. It can be subdivised into two categories:

  - Self-pollination, in which most part of the pollen of a plant fertilizes the female gametes of the same individual. Wheat is an example of self-pollinated crop. Self-pollinated crops are thus rather stable (mutations occur during the formation of seeds, but to a moderate extent), and a single specimen of the variety can easily duplicate.

  - Cross-pollination, in which most part of the pollen of a plant fertilizes the female gametes of another individual. Corn is an example of a cross-pollinated crop. Cross-pollinated crops are the least stable ones - however, it is quite likely that, except for hybrids, the seeds from a variety planted in a field will have characteristics that are rather similar to its parent plants' ones.

Self-pollinating plants sometimes cross-pollinate and reciprocally, but the resulting seeds are a negligible proportion of produced seeds.

The lack of appropriability justified the intervention and the crucial role of public action in the development and distribution of seeds and crops. For example, the US Patent Office acknowledged, in the early 19th century, that intellectual property rights and market incentives for private research in the agricultural sector were not sufficient to encourage private firms to innovate and develop new varieties and animals. This conclusion caused the Patent Office itself to start importing seeds and breeding animals from abroad, to make up for the failure of national R&D to encourage the development of plants varieties and animal breeds in the US (Huffman and Evenson, 1993). Hence, throughout the first half of the 19th century, the majority of productivity gains across the world had been obtained mostly by picking-up improved seeds from abroad (which, necessarily, provided varieties that proved to be poorly adapted to local conditions). Then, in the second half of the 19th century and until the late 1920s, plants have been improved, and seeds provided to farmers - generally for free - by governmental agencies. The relevant agencies adopted more scientific and systematic methods, and developed innovations that were more adapted to domestic conditions of production and demand. For example, in the United States, the second half of the 19th century saw the adoption of various Acts aimed at financing agricultural universities and publicly supported R&D (Fernandez-Cornejo, 2004).[2]

The possibility for breeders to capture some of the social value of their innovation arose in the 1920s with the discovery of hybridization. Hybrids are produced by the cross pollination of two pure inbred lines of plants (whenever the plant is androgenous, the male part of one of the lines and the female part of the other one are removed or hidden, to avoid self-pollination). Both lines have interesting characteristics, and the breeder aims to gather the characteristics of each line in

[2]The US Department of Agriculture has been created in 1862. The 1862 Morill-Land Grant College Act, strengthened in 1890 by the second Morill Act, created agricultural colleges and universities. The 1887 Hatch Act established the State agricultural experiment stations (SAES) to develop research in Agriculture and the 1914 Smith-Lever Act instituted the Cooperative Agricultural Extension Service. For more details, see Conkin (2008, Chapter 1) and Baker et al. (1963, Chap. 1).

a single plant. Provided inbred lines are well selected, the seeds that result from this hybridization process, called F1 hybrids, mix the characteristics of the parents. However, in some cases (especially when several genes code the desirable trait), most of the descendants of these F1 hybrids do not express such traits, and hence have no advantage over other available varieties[3]. In that case, the F1 hybrid is not replicable from any field growing this variety (the non-rivality and non-excludability criteria of public good are then violated), and its producer can easily capture a rent from its innovation. Of course, F1 seeds can be obtained easily from the inbred lines, so the possibility for the firm to extract rent depends heavily on its capacity to keep these lines secret. However, the inbred lines cannot be found out by retro-engineering from the mere observation of F1 seeds or plants. The first lines of hybrid varieties have been developed in the 1920s, and were first commercialized in the US in 1926 by the new founded Pioneer Hi-bred company (the first plant to be hybridized and commercialized was corn). The newly developed hybrid corn had several advantages over existing varieties (USDA, 1962): higher potential yields, stronger stems,[4] more uniform corn ears, etc. The diffusion process of hybrid corn started slowly, but the adoption rate had reached 95% in 1960 (Fernandez-Cornejo, 2004, Fig. 2). The wide spread of improved varieties (especially hybrids) and agricultural chemicals allowed significant increases in agricultural yields. In the US, corn yields increased from 20 bushels per acre in 1930 to roughly 120 in 1990 (Fernandez-Cornejo, 2004, Fig. 1). In developing countries, following the "Green Revolution" (Borlaug, 2007) yields of rice and wheat increased at a pace of 1% per year between 1970 and 1990 (Morris, 1998, Chap. 1). Between the origins of scientific plant breeding and the 1930s, crossing varieties had almost exclusively been undertaken by public actors. From 1930 on, the role of the private sector had emerged in producing hybrids, but breeding of conventional, non-hybrid varieties remained an almost exclusive field of public intervention. The public sector thus kept a major role in plant breeding until the advent of biotechnologies in the 1980s.

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[3]The following simplified reasoning explains why a hybrid descendent has a low probability to have the same qualities as its parents. By definition, a hybrid F1 is heterozygote - *i.e.* it has two different alleles, or "versions" of a gene -, at least for the genes that code the valued traits. Suppose the two alleles have the same probability of 0.5 to be transmitted to the descendant. Then for each gene, the probability that the offspring is heterozygote as well is only 0.5. Suppose, as well, that the process of picking a given allele is independent from the process of picking up all the other ones. Then, if n genes code the desired characteristic, the probability that the offspring has the same relevant heterozygote genotype is 0.5^n.

[4]Stronger stems make mechanization of cultures more profitable, because it makes plants less sensitive to lodging when machines browse in the fields.

Moreover, despite unquestionable role in providing innovation on varieties with some characteristics of a private good, hybridization has not brought perfect appropriability for research on all crops. Hence, it did not allow the emergence of a private market taking the role devoted to the public sector. Indeed, all plants cannot be hybridized profitably (among other factors, hybridization is easier on open pollinated crops - such as corn). Moreover, the offspring of a generation has only reduced vigor and may always be replanted, as long as it remains profitable for the farmers to replant less efficient plants instead of buying F1 hybrids after every harvest. For the development of private sector, appropriability thus had to be driven by the institutional framework as well. In order to stimulate further private investment in agricultural R&D, the 1970s and the 1980s saw the emergence of intellectual property protection over plants, in most major regions conducting R&D on varieties. This movement started with the enforcement of plant variety protections first, followed by the extension of utility patents to plants (cf *infra*).

1.2 Biotechnologies in agriculture[5]

The 1980s and, more sharply, the 1990s and 2000s, are characterized by an increase in privately-funded agricultural research (Alston et al., 2010, Chapter 6). This trend is particularly obvious for research on crops and seeds. Worldwide, between 1994 and 2010, private R&D on agricultural varieties more than doubled from 2006US$ 1,462 to 3,477 millions (Fuglie et al., 2011, Chapter 1). This trend coincides with the emergence of genetically engineered plant varieties. In the US, between 1979 and 2010, private R&D investment in varieties has been multiplied by 50, increasing from 43 to 2,179 million current US$. Simultaneously, average productivities of the crops that have been at the core of genetical engineering (namely corn, cotton and soybeans) have rapidly and significantly increased: +43% for corn, +41% for soybeans and +25% for cotton between 1989 and 2015 (USDA NASS, 2015).

The first introduction of foreign DNA in plant cells (an antibiotic-resistance gene introduced by a bacteria into tobacco and petunia cells), by various laboratories including Monsanto's, dates back to 1983. Then, in 1987, the *Bacillus thuringiensis* (*Bt*) gene - that became, in the late 1990s, one of the main genetically engineered

[5] For a broad, novel-style history of genetically engineered plants, see Charles (2002).

commercial successes (*c.f. infra*) - was successfully introduced into tobacco cells. During the same period, two herbicide tolerant traits were introduced into crops: glyphosate and glufosinate resistance (*c.f. infra*).

The 1980s are characterized by a vivid competition in research on genetical engineering from both US and Europe. As a consequence, the intensity and speed of patent races for genetically engineered plants dramatically increased. The first introduction of antibiotic DNA in plant cells involved both Monsanto, a US firm headquartered in Missouri, and the Max Planck Society, a German laboratory. *Bt* was first introduced into tobacco simultaneously by a researcher at Washington University in Saint-Louis, US, and Plant Genetic System (PGS) from Belgium. Also coincidentally, the Swiss firm Ciba-Geigy and its American competitor Mycogen patented their own *Bt* gene. Monsanto, and Calgene from California, both developed glyphosate resistant crops in the same period. At the same time, the German company Hoechst and PGS successfully introduced resistance to glufosinate into plant cells. Keeping in mind that almost exclusively successful firms and institutions are recorded, it is quite probable that the sector has been even more atomized than what these examples show. In 1993, Calgene commercialized the first genetically engineered product ever, the Flavr Savr tomato (cf *infra*), that turned out to a commercial fail. Hence, commercialization of genetically engineered seeds actually begun in 1995, with Ciba-Geigy's *Bt* corn, Calgene's bromoxynil tolerant cotton, and Monsanto's *Bt* cotton, *Bt* potato and "Roundup Ready" soybeans.

In the early 1990s, with the first commercialization of genetically modified (GM) crops, several holders of patents over genes licensed to seeds producers the right to insert them in the crops varieties they had conventionally bred and sold before. In 1992, Pioneer Hi-Bred - who had not been involved in the 1980s race for patents over genes - paid Monsanto to be able to insert its glyphosate tolerance ("Roundup Ready") gene into its own soybean seeds. Hoechst allowed, with neither licence agreement nor particular restrictions, plant breeders to insert freely its glufosinate tolerance ("LibertyLink") gene into their seeds. Such scheme was profitable even without royalty or license fee, because each firm owned the patent over both the gene and the herbicide (Glyphosate is the main active principle in Monsanto's Roundup, and glufosinate is the active principle of a series of Hoechst's herbicides including Liberty and Basta). In 1993, Monsanto sold the right to insert *Bt* genes into corn to Pioneer and into cotton to Delta and Pine Land Company.

The late 1990s and the 2000s saw a wide movement of mergers and acquisition in the biotech sector, which has resulted in a stronger concentration of the GM crops market, and the association of GM crops majors with stronger, larger firms. This movement triggered the emergence of large firms producing simultaneously genetically engineered crops and agrochemicals. After the fail of Flavr Savr, Monsanto bought Calgene in 1995. DuPont, a chemical producer, bought Pioneer in 1999. Hoechst merged with PGS to become AgrEvo in 1994, a part of Aventis in 1999 that was bought by Bayer in 2002. Ciba-Geigy and Sandoz merged into Novartis in 1996, and became Syngenta after its merger with the agrobusiness part of Astra-Zeneca in 2000. Mycogen has been taken over by Dow Chemicals in 1998. Simultaneously, counteracting the trend of licensing to independent seed companies that had prevailed in the early 1990s, biotech firms started absorbing seed producers from 1996 on. Such movement among the major GM R&D firms was launched by Mycogen, who absorbed various seed companies, starting in 1992. Monsanto took over Asgrow in 1996, DeKalb in 1998 and Delta & Pine Land in 2007.[6]

It is more difficult to draw a general, global trend for public R&D on varieties, as it is much more country specific than the private sector worldwide race for development of GM crops. As noted by Pardey et al. (2014), between 1981 and 2000 publicly funded R&D in agriculture in general almost doubled (from 14.24 to 20.3 billion US$, inflation adjusted), and the major part of the increase occurred in the developing and emerging countries (they spent 41% of public agricultural R&D in 1981 and 50% in 2000). In developing countries, public spending accounts for almost all agricultural R&D effort (6.4% only of agricultural R&D was private in 2000 in developing countries), which, more generally, faces a chronic underinvestment (James et al., 2008). The main role of public research in developing countries remains to develop and supply varieties adapted to local conditions (consumers needs, soils, climate, etc.), which would not be profitable enough for private firms - either local firms or from developed countries. In developed countries, it appears that the strengthening of the private sector has led to more complementarity between private an public research, especially on seeds and crops (Heisey and Fuglie, 2011). For example, in the US, private research focuses on most profitable varieties (mainly corn, but fruits and vegetables, soybeans and cotton as well) for which research returns

[6]This paragraph merely presents a few examples to exemplify the exposed trends. For a more exhaustive and synthetic presentation of the strong movement of concentration in the seed industry between 1995 and 2010, see Chapter 2 in Fuglie et al. (2011), and especially fig. 2.2.

are more appropriable (*i.e.* plants that are not easily duplicable such as tuber propagated or self-pollinated ones) while the public sector focuses on the remaining ones (Fernandez-Cornejo, 2004; Heisey et al., 2001). In addition, public research is dedicated to more fundamental research (on breeding methods or germplasm conservation and enhancement), and private research is oriented towards commercial applications (Heisey et al., 2001).

2 Highly productive varieties developed and commercialized by a concentrated private sector

Half of the agricultural R&D effort on varieties now focuses on biotechnologies and genetically engineered plants, and most of the potential for future innovation in plant varieties, as well, is concentrated in this technology. Research on GM crops is now essentially undertaken by the private sector, in a very concentrated market, which has various, and rather uncertain consequences on the market for innovations.

2.1 R&D on plants varieties has allowed the development and adoption of highly productive varieties

Research on genetical engineering in agriculture has made possible the identification, and introduction in existing plants, of genes that develop specific, valuable traits. For a long time, breeding of improved crops has been based on crossing varieties, which has allowed significant increases in plants productivity. Built on both “conventional breeding” and, since the 1980s, on genetical engineering as well, modern varieties of plants have driven significant increases in cultures productivity. Fuglie et al. (1996) found that genetic improvement of varieties have largely contributed to productivity gains in the US. For instance, 50% of the 1.13% average annual yield increase in wheat cultivation over the 1975-1992 period can be attributed to newly developed varieties - the remainder is due to improvements in processes and innovations on other inputs (chemicals, irrigation systems, machinery, etc.). More generally, Fischer and Edmeades (2010) estimated that improved varieties have driven an average increase in cereal yields between 0.5% and 1% per year since the 1980s - which is consistent with the findings of Duvick (2004). Evenson and Gollin (2003b), summarized in Evenson and Gollin (2003a), studied the pattern of agricultural yields in developing countries. They showed that the diffusion of modern varieties (MVs) with enhanced characteristics has been a continuous process from the early 1960s to the late 1990s. International agricultural research centers (IARCs) have played a major role in this process (almost 50% of MVs have been either developed in IARCs directly, or involve a parent line developed in such centers). During the “early Green Revolution”, between 1961 and 1980, 21% of the growth in yields (which averaged 2.5% per year across all developing countries), and 17% of the growth in output growth may be attributed to MVs. During the “late Green Revolution”, between 1981 and 2000, the contribution of MVs accounted for almost 50% of the 1.8% average annual increase in yields across developing countries, and 40% of output growth.

Genetically modified crops deserve a specific attention because they represent a large share of both investments in R&D on varieties and outcomes of this R&D and account for much of the productivity gains achieved in agriculture since the 1990s. According to RoAPE (1998), genetically engineered seeds can be classified into three generations:

- First generation: crops with traits modifying inputs use. These crops allow farmers to modify their mix of inputs (pesticides, herbicides, or fertilizers), as the traits belonging to this generation give special features to the plant itself. Herbicide tolerant and pest resistant crops are the most widely cultivated crops in this generation. Herbicide tolerant (HT) crops allow farmers to spread wide-range, non selective herbicides over their cultivated areas, without having to target weeds precisely as required with conventional crops to avoid killing them with the weeds. The herbicides for which tolerance traits have been developed are glyphosate (commercially known as Monsanto’s Roundup) or glufosinate (commercialized under several brands as Basta or Liberty). Pest resistant crops produce, without farmers intervention, one or several pesticides that are toxic to some of the crops’ natural predators. The most common insect resistance is based on the emission of different forms of *Bacillus thuringeiensis* (*Bt*), which is lethal to various insects - among them, the European corn borer, several stemborers and the corn rootworm (Romeis et al., 2008). Belonging to this first generation, virus resistance traits have been developed as well, although their commercial success so far has been weaker than HT and *Bt*.

Most of these traits are still in their development phase (Halford, 2006). for instance, drought tolerance can be obtained by genetical engineering, as for Monsanto's MON87460 maize. The technology has not fully developed its potential yet, however. Crops tolerant to other abiotic stresses (heat, salt, etc.) are also under early stages of development and are likely to be available in the next decade (Qaim, 2009).

- Second generation: crops with specific output traits. In contrast to first generation ones, second generation traits give specific characteristics to the product of the plant, and not to the plant itself. The first GM crop that was (unsuccessfully) commercialized actually belonged to the second generation: Calgene had introduced in its Flavr Savr tomato a gene delaying the fruit's decay - this was supposed to allow farmers to leave the tomatoes on their plant longer, considerably improving their taste. After the introduction of the Flavr Savr tomato in the early 1990s, few significant attempts to commercialize second generation traits took place over the next 15 years. However, second generation of GMOs regained attention recently, with the very interesting and promising introduction of enhanced nutritious capacities in agricultural output, named "biofortification". A very well known biofortified GM crop is the "golden rice", a variety of rice enriched in vitamin A developed in the early 2000s for non-profit diffusion by the Philippines' International Rice Research Institute. For several reasons (lack of public acceptance, cautious regulation of GMOs, etc.), the golden rice is still in its development phase, and was still not commercially available in 2016 (Philpott, 2016). Several second generation GMOs are to be released in the coming years, including "functional foods" (*i.e.* "foods that provide health benefits beyond basic nutrition") with enhanced fatty acid profile, increased vitamin or mineral contents, etc. (Pew Initiative on Food and Biotechnology, 2007).

- Third generation: crops producing output whose main use is neither food nor fiber. This last generation of GMO traits are those that make the plant produce a valuable output (in general, a molecule) that it does not produce at all naturally, without the GM trait. The plant is thus used as a "molecular farm" (Moschini, 2006). Such output can be either plant-made pharmaceuticals (PMPs) or plant-made industrial products (PIMPs). Some specific proteins are already produced using GM plants - for instance avidin, which has

> been the first PMP to be produced, in the late 1990s (Hood et al., 1997), aprotinin and trypsin (Howard, 2005). However, only a very limited share of third generation genetical engineered crops are exploited, and many of them are currently “in the pipeline” of R&D firms (Qaim, 2009). PMPs production, often referred to as “pharming” or “biopharming” is the major share of third generation GM crops R&D currently undergoing, and, among them, the development of antibodies and vaccines is particularly advanced and promising on short to middle term. Pharming provides an opportunity to produce, at a much lower cost and/or with much weaker side effects, pharmaceutics for which laboratories used to rely on either natural processes, or host systems other than plants (microbes, yeasts or animals). PMIPs, despite a less advanced development than PMPs, benefit from a broad spectrum of potential applications: GM crops can produce enzymes used in the production of paper and textile, proteins such as collagen, and biodegradable plastics (Moschini, 2006).

Although it is easier and potentially more profitable to introduce a given trait in some plants than in others, the development of GM traits is rather independent from the plants they are subsequently inserted in. This explains why genetical engineering is a complement, rather than a substitute, to conventional breeding. As stated by Qaim (2009), “the benefits of GM can be fully realized only when the technology is inserted into a number of locally adapted varieties”.

Despite lingering public concern, the share of GM crops in total cultivated surfaces globally has increased every year since the first commercialization of this technology in 1996. Cultivated surface increased from 1.7 million hectares in 1996 to 181.5 millions in 2014 (James, 2015), which represents around 13% of the 1.396 billion total arable land (FAO, 2016). Biotech firms and seeds suppliers commercialize several crops that stack more than one GM trait, sometimes belonging to different patentees: according to James (2015), 28% of GM planted surface have stacked GM traits (*e.g.* crops mixing several *Bt* genes, or herbicide tolerance and *Bt* traits). GM crops production is concentrated in some regions of the world: the US cultivates 40% of global GMO area, North America and all Americas concentrate 47% and more than 87% of it, respectively. The European Union cultivate negligible surfaces of GM crops (these are banned in most member states), with only Spain dedicating a significant area to GM cultures (James, 2015).

The development of GM crops has led to significant yield gains. For instance, Moschini et al. (2000) estimate that cost reduction induced by Roundup Ready varieties in Iowa state in the US lies between 15 and 28 US$ per hectare, depending, of course, on the quantity of herbicide used prior to the introduction of the new variety. In a meta-analysis of 147 published studies on biotech crops, Qaim and Klümper (2014) find that this technology increased crop yields by 22% on average. It should be noted, however, that the dispersion of yield increases and, even more, efficiency gains may be significant (Gouse et al., 2004). For instance, the advantage of *Bt* varieties over non-*Bt* ones depends heavily on several factors: pest pressure, initial amounts of pesticides spread, initial number of spreading campaigns, spreading techniques, etc. The modification of input mix triggered by GM crops has reduced the cost of agricultural production (decreasing the expenditures on chemicals, labor and machinery) and increased farmers' aggregated profits (Qaim, 2009). It has also led to significant transformations of agriculture's environmental impact, that will be examined *infra*.

2.2 Concentration in the private sector of R&D on plant varieties

A striking feature of the sector of plant varieties is its concentration: few firms control most of the market for GM traits. The movement of concentration has been quite fast, and occurred in the late 1990s and early 2000s. Before a massive wave of mergers and acquisitions among the agricultural biotech firms, the market of seeds and crops was rather atomized. Numerous small firms and start-ups owed a significant market share: in 1995, 37% of the total value of seeds throughout the world were sold by the 10 largest seed producer firms.[7] In 2009, this figure had increased to 73%. Monsanto and DuPont (Pioneer) accounted for 27% and 17% respectively, and more generally United States firms' market share was higher than 50% (Fuglie et al., 2011). This concentration trend is more obvious in some sectors: on the vegetable seeds market only, the top 8 companies accounted for 94% of global sales in 2007 (Heisey and Fuglie, 2011). Finally, for some specific seeds and crops, figures are even more striking: in 2007, 85% of global GM crops cultivated surfaces held a Monsanto trait, and 98% of these surfaces held traits

[7]Monsanto, DuPont (Pioneer), Syngenta, Limagrain, Land O'Lakes, KWS AG, Bayer, Dow, Sakata and DLF-Trifolium.

developed by 5 firms (Monsanto, DuPont, Syngenta, Bayer and Dow).[8] Figures on intellectual property protection granted over plant varieties, as provided by Pardey et al. (2013), complement this picture: while 55% of total IP rights over plants were held by private companies in the 1930s-1940s (almost all the remainder accruing to individuals), this figure soared to 82% in the 2003-2008 period.

It is quite remarkable that the major seeds and crops companies are also the major investors in R&D on varieties (one only notable exception is BASF, whose R&D effort on varieties is comparable to Bayer's, despite the fact their direct sales of seeds and crops are negligible). In the early 1990s, most of R&D effort on seeds and crops (GM and non-GM) was undertaken by large, traditional seed companies focused almost exclusively on plant breeding. In 1994, they represented 66% of the total of 2006US$ 1,462 millions spent by private actors in R&D on varieties, while the aggregate of firms producing both seeds and chemicals, the "Big 6", accounted for 22% and small and medium biotechnology firms for 11%."[9] In the early 2010s, however, both the absolute and relative R&D effort of traditional seed companies and small and medium biotechnology firms had decreased. In 2010, they accounted for 21% and less than 3%, respectively, of the total 2006US$ 1,462 millions spent in crops R&D by private actors. On the contrary, the "Big 6" firms had taken the major part of effort, as their share had increased to 76% (Heisey and Fuglie, 2011). These figures are quite consistent with the historical trend towards concentration of the market in the hands of large seeds and chemical firms. First, the seed market has shifted from traditional varieties towards more and more GM crops. Second, most biotech firms have either been chemical producers before 1980 (*e.g.* Monsanto or Hoechst) and/or largely merged with or been bought by chemical firms (*e.g.* Pioneer bought by DuPont or Mycogen bought by Dow). Heisey and Fuglie (2011) finally note that the major seeds firms have cross-licensing agreements with each other (especially those inherited from the agreements signed in the 1990s, for example between Pioneer and Monsanto on Roundup Ready and *Bt* traits). It is also notable that the "Big 6" firms hold together 71% of market shares on agro-chemicals sales (Shand, 2012). Heisey and Fuglie (2011) estimate the share of R&D dedicated to biotechnologies (opposed to the share of R&D dedicated to conventional breeding) to have been around 50% in 2003.

[8]It should be noted, however, that some crops are "stacked", *i.e.* they gather different GM traits.

[9] The Big 6 is a pool of firms composed of BASF, Bayer, Dow, DuPont, Monsanto and Syngenta - or, especially before 2000, the firms that, after mergers, gave birth to these ones.

The concentration of the private sector conducting R&D on varieties may have had several economic consequences - although, due to a lack of both available data and studies, it is difficult to draw anything further than conjectures. Shand (2012) highlighted several negative consequences of concentration on the R&D market, and her paper is a useful starting point to discuss the possible impacts of the agricultural R&D sector concentration movement on the agricultural markets. First, based on the conclusions of Fernandez-Cornejo and Schimmelpfennig (2004), Shand noted that concentration has had a negative outcome on the intensity of agricultural R&D. Theoretically, concentration may have opposite effects on research intensity:

- In favor of innovation. Economies of scale allowed by concentration make innovation more profitable. First, conducting research implies significant fixed costs, and past experience enhances skills and processes of laboratories and researchers, which has positive effect on future R&D. Second, searching for new varieties often involves working on various previously patented innovations, which requires licensing agreements. Yet, negotiating with few actors is less costly than negotiating with numerous ones. Third, monitoring costs for patent infringement may be significantly lower when less competing firms have to be monitored. Fourth, economies of scope drive costs down as well: once a trait is developed for a given crop, it is less costly to adapt it to other crops.

- Against innovation. First, atomization of R&D firms induce a pressure among them to innovate, because threats that a product is made obsolete by more recent options are more pregnant. In order to remain at the technological frontier, a firm has to keep innovating. Concentration mitigates such threats, and hence reduces this incentive. Nevertheless, it should be noted that this argument has an immediate counterpart: when competition among innovators is stronger, the expected profit an inventor can capture from discovering an innovation is eroded (as it is threatened by more competitors), and innovation may thus appear less profitable to the patent race runners, which can discourage R&D effort (Loury, 1979). Second, large, oligopolistic firms may also be more risk adverse than small, atomized ones.

An econometric analysis by Schimmelpfennig et al. (2004) found a "simultaneous self-reinforcing relationship" between market concentration and reduction in R&D

intensity (as measured by the ratio between the number of field testing applications for GM varieties and the seeds sales). Acknowledging a correlation between the movements of concentration in the varieties R&D sector and R&D intensity, Schimmelpfennig et al. investigated the question of causality in this observation. Their analysis focused on corn, cotton and soybean, which are the four major GM crops(Fernandez-Cornejo and Schimmelpfennig, 2004). They found that concentration reduces R&D intensity on the crops they study. However, at least three objections that are not taken into account by this study may dampen its results. First, the field testing application that is used to measure R&D effort occurs rather far in the R&D process.[10] This indicator is thus a rather imperfect proxy for actual R&D intensity, because the numerator of the ratio of field testings over seeds sales may have fluctuated, following R&D cycles, independently from concentration movements.[11] Second, as genetical engineering was starting from scratch in the 1980s, firms that were active in the R&D sector produced negligible quantities of seeds. They started significant commercialization only after completion of the research process. Hence, the denominator of the ratio increased, independently from concentration fluctuation, because the new crops were released on the market. Third, reverse causality may occur as well: increasing R&D effort by some firms may be a way to get rid of those competitors that cannot follow the movement. More generally, as pointed out by the authors, intertemporal strategies of firms, that are not captured by the static model specification, may change the rate of innovation. More empirical work is hence needed to conclude on the argument that stronger concentration causes less R&D effort.

A very interesting potential consequence of concentration in the agricultural biotechnologies sector has been highlighted by Leonard (2011). According to him, concentration makes it possible for a dominant firm A (Monsanto in this case) to insert a special clause in its licensing contract with a smaller firm B. Such clause prohibits firm B from introducing in its seeds any trait from a competitor of firm

[10]See p. 53 in Fernandez-Cornejo (2004) for more details on the steps of crops innovation process.

[11]Two polar cases exemplify this reserve. The first one occurs at the beginning of the innovation process, when many firms are competing to develop a new trait. The R&D effort undertaken at the aggregated level by all these firms is important, but only the most successful ones, representing only a small share of the total effort, will be able to run field trials. The second one occurs at the end of the innovation process, after a new generation of traits is developed and well known by its developer, and its scope is extended to other varieties. Then, the R&D effort is essentially dedicated to adaptation of the traits to the varieties. It is quite likely that, precisely because the trait is well known, less trials will be needed, and thus a smaller share of this R&D effort will translate to field testing than when the trait itself was under early development.

A. Of course, it is acceptable by firm B only if firm A is big enough and offers a large portfolio of traits so that firm B foresees the possibility to introduce other traits in its seeds later, when set on the market. However, beyond the fact that such agreement secures revenues to firm A as long as firm B remains operating on the market, it gives a significant advantage to firm A when the owner of firm B wants to sell it. Indeed, no competitor of firm A would be interested in buying a firm which cannot introduce any of its own traits in the production of crops. The legality of such licensing agreement has still to be evaluated by Courts, but their private and social legitimacy and implications would probably deserve further economic study.

According to Shand (2012), concentration has resulted in higher seed prices and has practically restricted research to 6 major crops (corn, cotton, soybeans, canola, sugarbeet and alfalfa) and two major GM traits (herbicide tolerance and insect resistance, cf *infra*). These facts are actually observable indeed: seeds prices have more than doubled between 1990 and 2010 (Fuglie et al., 2011, Figure 1.3), and most R&D is undertaken on soybean, cotton, corn, canola, sugarbeet and alfalfa (National Research Council, 2010). However, the responsibility of private sector concentration in these observations is not obvious. Even in an atomized market of innovators, patents would have caused seed prices to increase.[12] The focus of R&D on a narrow set of crops appears to be mainly driven by their relative advantage over other crops, and hence adoption rate by farmers (National Research Council, 2010, Introduction), or environmental regulations (for instance, herbicide resistant crops are not allowed where genetically close weeds are widespread, to avoid resistance transfer) (National Research Council, 2010, Chap. 2). It also appears that the GM traits that concentrate most attention were the easiest to work on when genetical engineering on plants emerged (Charles, 2002). It is thus not sure that a more atomized market would have developed other traits. Moreover, several other traits are under development, including by large firms (drought resistance developed by Monsanto, for instance).

[12]This increase in seed prices may have been either mitigated or strengthened by concentration (compared with an atomized market with patents). As R&D costs account for an important share of seeds prices, all drivers of R&D costs reduction due to concentration mitigate price increase. Stronger market power of concentrated firms may strengthen price increase, compared to atomized ones. However, market power is given by patents whatsoever. As patented varieties are hardly substitutable because of important patent width in most countries where GMOs are cultivated - cf *infra* -, its is quite likely that concentration does not add significant market power with respect to patents only.

She also states that concentration had large consequences on the marginalization of public sector research, and that is has limited the possibility for public researchers to conduct researches on protected varieties. As we saw in the previous section, the sharp increase in private R&D effort has been accompanied by a stagnation of publicly funded research (resulting in a decrease in the share of public research in total R&D on varieties). Yet, the causality in this observation is not obvious *a priori*, and it seems no serious empirical analysis allows to give a definitive answer to this debate. The point that the evolution of agricultural R&D resulted in more difficulties for researchers (from both the public and private sector) to lead research on protected varieties is a general drawback of intellectual property protection over innovation that would have happened, because of intellectual property protection, even in a less concentrated sector. It is even probable that on this point precisely, concentration is slightly socially beneficial, as researchers have to negotiate licensing agreements with fewer firms, which reduces transaction costs. Indeed, according to Santaniello et al. (2000), dozens of protected processes and products are used to develop a GM trait, and the more numerous actors holding the corresponding patents, the higher the costs to negotiate licensing agreements with them. According to National Research Council (2010), concentration may also explain a reduced availability of non-biotech seeds. Indeed, for small and atomized crops suppliers, commercializing only few GM crops and several non-GM crops, diversification strategies impose to keep commercializing the conventional varieties, even if they prove less profitable than the GM ones, while for large firms holding patents over several GM crops, their portfolio may prove sufficiently diversified with biotechnology varieties only.

Finally, Shand points out that concentration had negative externalities on environment, through the development of pest resistance to the newly developed crops. The environmental externalities of new GM varieties will be discussed in further details in section 3. Whatever, although it is more than probable that the fact R&D over GM crops is mainly led by private firms has environmental consequences, the role of concentration on these environmental externalities would deserve further discussion. Overall, the arguments mobilized by Shand seem to apply more to the fact that the research on GM crops is dominated by a private sector protected by strong intellectual property protection, than to its concentration in few firms' hands.

3 Different channels for the impact of plant varieties R&D on the environment

The environmental footprint of agriculture is considerable. Agriculture is responsible for roughly 29% of global greenhouse gas (GHG) emissions (Vermeulen et al., 2012): emissions from the agricultural production processes themselves (including crops, livestock and fisheries), from forestry and land use (including land conversion) and from the use of energy in agriculture (CO_2, methane and other GHG from burning fuel and consuming electricity in machinery, irrigation, etc.). The application of chemicals on the fields (pesticides, herbicides and fertilizers) erodes environment quality both on farm and off farm. The conversion of wild land to agriculture harms biodiversity. R&D on plant varieties modifies the consumption and mix of inputs, and, this way, has a strong influence on the agriculture environmental footprint (Hertel, 2012). In addition, the wide diffusion of new varieties may reduce the diversity of crops and flow of new genes to wild varieties. Finally, innovation to fight agains existing pests exert pressure on them, causing pest adaptation and modifying wild organisms structures.

The present section reviews the environmental effects of agriculture that are relevant to consider in order to analyze the externalities of R&D on crops. Each subsection examines one effect, and reviews the mechanisms though which R&D on varieties can turn into one or various environmental impacts. Although most of the environmental effects of agricultural production are acknowledged by a large consensus in the literature, their magnitude, and, thus, the overall environment impacts of agriculture are, in general, more debated. Hence, the potential impact of R&D on varieties we review in what follows should be considered with caution.

3.1 The role of crops R&D in sustainable intensification and land sparing

Some authors have suggested that limited land supply will require a strong intensification of cultures to ensure food security for 9 to 10 billion people, the population forecasted to inhabit the world by 2050 (Smith et al., 2010; Godfray et al., 2010). Intensification is “the increase of agricultural production per acre of land dedicated to agriculture that - through fertilization, irrigation and pesticides use - has an impact on ecosystems, altering biotic interactions and limiting resource availability" (Matson et al., 1997). Roughly 40% of globally available land area is dedicated to agricultural production. Moreover, agricultural R&D has been a key driver of increases in yields for decades (Pardey et al., 2014) and is expected to allow further increases (Godfray et al., 2010). Hence, it has a large role to play in intensification, and thus in controlling the environmental impact of agriculture. It has long been acknowledged, indeed, that intensification has large consequences on on-farm and off-farm environment (Matson et al., 1997; Morton et al., 2006; Matson and Vitousek, 2006; Vandermeer and Perfecto, 2007). The pressure of agriculture is particularly strong on tropical ecosystems, as they remain in a much more native shape than agricultural land in developed countries (Ranganathan et al., 2008; Nepstad et al., 2008). Simultaneously increasing yields, nutrient-use and water-use efficiency, maintaining soil fertility, and sustainably enhancing diseases and pests control will most probably not be achieved by market mechanisms only, and will require policy intervention to take agriculture's externalities into account (Tilman et al., 2002).

The question of intensification has recently regained interest in the biodiversity preservation debate with the introduction of the *sustainable intensification* concept (Cassman, 1999; The Royal Society, 2009; Beddington et al., 2012). Sustainable intensification is defined as a set of "practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered" (Tilman et al., 2002). A mix of solutions will certainly have to be implemented in order to meet the needs of an 8 to 10 billion world population in the second half of the 21$^{\text{th}}$ century: redesign of diets, waste reduction, increase in production, etc. Deciding the relative importance of each solution in this mix belongs to policymakers. However, if increase in production is, as it is quite likely, chosen as a major component, the capacity of agriculture to double in the next 50 years is a general consensus - however, it is much more discussed that such target could be reached sustainably (Balmford et al., 2005; Ewers et al., 2009).

Biodiversity is an important aspect of environmental impacts of agriculture (Foresight, 2011, Chapter 8) and, as a consequence, of sustainable intensification. On this topic, the *land sharing/land sparing* debate is a central one. To produce a given output of agricultural commodity on a constrained surface, technology being given, two polar strategies can be considered: producing as much as possible on the smallest area, and leaving the uncultivated remainder for wildlife, or spreading production uniformly over the whole surface. The first option, that implies a strong intensification on the cultivated land but allows to save the uncultivated land from any human intervention is referred to as *land sparing*. The second option, that implies an average intensification on any piece of surface defines *land sharing*. Waggoner (1996) first suggested that intensifying agriculture strongly on limited areas could "spare land for nature". He asserted that to do so, several paths should be followed, ranging from more vegetarian diets to the development of varieties offering higher yields. Intensification is one of these paths. The discussion on *sharing/sparing* has been formalized by Green et al. (2005). They suggested a decision rule between "sparing" and "wildlife-friendly" (*i.e.* sharing) farming that depends on the shape of the relationship between biodiversity density and intensification. If biodiversity density is a concave function of intensification, sharing is preferable. If it is a convex one, sparing is. Indeed, if the function is convex, a lot of species are lost in the low levels of intensity but the marginal effect of intensity on the species decreases rather rapidly. Spreading intensity uniformly over the available surfaces would thus cause important species losses, and it is more sensible to sacrifice almost all species on a limited piece of land, because it allows to save all species on the remaining uncultivated surface. Reciprocally, if the function is concave, the marginal effect of intensity on losses of species becomes really significant for high intensity only, and it is thus sensible to avoid largely intensive cultures as much as possible. Fischer et al. (2008) extended the analysis developed by Green et al. (2005), comparing the use of sharing and sparing in the real world. They observed that some regions tend to adopt a sharing approach (with large, industrialized intensive farms, in the middle of extended uncultivated areas - *e.g.* in Western Australia), others tend to adopt a sparing one (with small, "spatially continuous" and not very intensive cultures - *e.g.* in hilly landscape in Costa Rica), with a large continuum in between (*e.g.* in Northern Europe). They highlighted the causal role of topography, overall productivity of land, historical land ownership, investment capacity of farmers and public policies in these trends in agriculture choices.

Whatever the optimal balance between land sharing and land sparing, the latter, at least, relies strongly on high yields. Agricultural R&D being a crucial determinant of yield increase, it is a central actor in this debate.

3.2 Crops R&D and greenhouse gas emissions

Agriculture's share in total emissions of greenhouse gas emissions is considerable. Such observation *a priori* gives a strong potential role for R&D on crops to modify agriculture's GHG footprint. To discuss this role, it would be important, first, to understand the composition of agriculture's emissions. Second, it would be necessary to understand the influence that R&D on agricultural varieties has on the various origins of emissions.

This paragraph focuses on agricultural production process's emissions, excluding land use conversion issues that will be considered *infra*. Figures quoted are for 2011 and come from the estimations by Tubiello et al. (2014). Excluding energy use, forestry and land use conversion, agriculture emitted 5.335 billion tons equivalent CO_2 of greenhouse gases in 2011. Most of them came from livestock activities, on which R&D on varieties should not have a large impact, at least in the short to medium term:[13] enteric fermentation ("produced in digestive systems" of cattle, 2 080 million tons of CO_2 equivalent) and manure left on pasture (1186 Mt CO_2 eq). However, the origin of the remaining emissions lies in mechanisms that can be influenced by R&D on crops. When spread over fields, synthetic fertilizers emit nitrogen dioxyde (N_2O), and it is estimated they accounted for 725 Mt CO_2 eq. The decomposition of culture residuals in rice paddy fields emits CH_4, which represented 523 Mt CO_2 eq. The decomposition of crops residues on cultures generated 197 Mt CO_2 eq., and 29 Mt CO_2 eq came from burning crop residues as a technique of cleaning and fertilization of soils. Spreading manure over soils emitted 185 Mt CO_2 eq, and cultivation of organic soils was responsible for 133 Mt CO_2 eq. Finally, burning savanna (mainly in Africa, and to some extent in Oceania) emitted 288 Mt CO_2 eq. Although an important share of it is made for extension of pasture land, some is dedicate to the extension of cultivated land, on which R&D may have an influence (cf *infra*). No relevant data is available for energy use by crops cultivation only, but Tubiello et al. (2014) gave an aggregated estimation of energy use, including livestock and fisheries, of 785 Mt CO2 equivalent.

The impact that R&D on crops has had on land use will be examined in section

[13] R&D on varieties may develop, in the future, improved animal feed - *e.g.* a second generation GM crops - that reduces the CO2 emissions caused by enteric fermentation and manure spread, without weakening the nutritional quality of the feed. However, it does not seem to happen soon, and does not appear as a priority for breeders for now.

3.4, but whenever R&D allows to save land use from agriculture, it has a positive impact on GHG emissions. The conditions for R&D to save land are too complex, however, to state that, in general, it has had, or has not had, a positive impact on GHG emissions through this channel. On the contrary, it appears that the overall effect of recent crops R&D on GHG through chemical use has been positive (the impact of R&D on varieties on chemical use will be explored into more details in section 3.3). Indeed, R&D on varieties seems to have reduced chemicals use, on average, and production of chemicals emits GHGs while application over fields requires fuel-powered machinery. New varieties have also had a positive influence on greenhouse gas emissions through different practices of tillage. This has reduced the need for tilling (Brookes and Barfoot, 2014). Conventional tillage practices require tractors to go through the fields, consuming fuel, and the withdrawing of crop residue and weeds from the soil frees back sequestered carbon. Farmers cultivating herbicide tolerant crops are more likely to adopt conservation tillage (either no or partial tillage): Mcbride and Fernandez-Cornejo (2002) showed that in 1997, 60% of cultivated area of GM soybeans adopted conservation tillage, compared to 40% for conventional soybeans cultivated area. 40% of GM cultivated area was not tilled at all, while the figure for conventional soybean was 20%. Brookes & Barfoot estimated that no tillage allows to save around 50% of total fuel consumed in the agricultural production process, compared to conventional tillage (Tables 61 and 62). Highlighting the relevant cautions on the estimation methods, Brookes & Barfoot provided estimates for the net carbon sequestration allowed by reduced and no tillage practices (Table 64). Although this sort of figure should be taken with a similar care as figures on land use (cf *infra*), they estimated that GM crops allowed to save 16.8 billion tons of CO_2 equivalent from fuel savings and 203.6 billion t CO_2 eq. from change in tillage practices since 1996. It is also notable that reduced tillage reduces soil erosion as well (Lutman and Berry, 2006).

3.3 Crops R&D and chemicals use

One of the most mediatized environmental impact of agricultural production occurs through the use of chemicals, pesticides, herbicides and fertilizers. Whether the outcome of R&D on varieties will allow to reduce the use of chemicals is thus a central question for agricultural innovation's environmental consequences.

The first goal of pesticides is to increase agricultural output in presence of pests. In contrast with this benefit, they cause several side effects, adding to the private cost of acquiring them. Spreading them on agricultural fields has a various range of consequences on the environment in general, and health in particular. Though such figure requires highest caution, Pimentel (2009) estimated the total environmental and social costs from pesticides in the United States to be US$9,645 million per year.[14] In a survey of existing literature, Pimentel suggested a typology of the numerous environmental impacts of pesticides use. In his study, impacts fall into eight categories:

- Direct impact on human health: either direct poisoning caused by ingestion of pesticides or chronic illnesses caused by exposure to such products. Pimentel (2009) estimated that almost 30 million cases of poisoning, and among them 220,000 fatalities, are recorded every year due to pesticides exposure. The negative consequences of ingestion or exposition to pesticides can be various, including on neurological, respiratory and reproductive systems (Hart and Pimentel, 2002). The carcinogenicity of some pesticides has been acknowledged by the American National Research Council (Archibald, 1989): 18% of insecticides and 90% of fungicides have been found to be carcinogenic, and farm workers and pesticide applicators face a statistically higher occurence of cancer than the average population. Pesticides can cause damages on human health through direct exposure where they are spread (especially for farmers and applicators) or indirect exposure (mainly transportation of residual pesticide away from the treated fields and pesticides residues in food).

- Destruction of beneficial natural pests predators and parasites that control pests naturally. The spectrum of pesticides is hardly narrow enough to focus on pests solely. They often destroy other organisms that would be beneficial to pest mitigation.

- Pesticide resistance in pests. Nature is able to "react" to the application of pesticides, developing new pests on which pesticides have a lower impact (a focus on this environmental consequence of pesticides application will be developed *infra*). The use of pesticides causing adaptation and destruction of pests predators, their efficiency decreases with application, requiring more and more pesticides to be spread to maintain their efficacy.

[14]See table 4.6 in Pimentel (2009) for a more detailed presentation.

- Crop destruction and production losses. To be efficient and harmless to crops, many pesticides require a careful spread, and misuse of pesticides can have two main consequences. An excess of pesticides or application in inadequate soil and/or weather conditions may reduce crops growth. Pesticides may drift from fields and contaminate other agricultural production (especially meat, eggs, milk, fish, etc.) beyond legal thresholds (regulators, such as the US department of agriculture, define acceptable quantities of pesticides in these products and monitor production to detect eventual over-content).

- Ground and surface waters contamination. Excess of pesticides that does not remain on the crops sometimes streams to ground and surface water. EPA (1990) surveyed drinking water wells (WW) and community water systems (CWS) in the US and found significant presence of nitrogen (a fertilizer, cf *infra*) in 57% of WW and 52% of CWS. It also found that 10.4% of CWS and 4.2% of WW contained at least residuals of one pesticide.

- Fishery losses. The off-farm transportation of pesticides to water can either directly contaminate fish, or indirectly destroy essential fish foods (*e.g.* insects). This negatively affects the production of fisheries.

- Destruction of wild birds and mammals. Several studies have pointed out the role of agricultural intensification in the decline of birds populations - for instance, see Donald et al. (2001). Although pesticides are not the only factor of agricultural negative impact, direct poisoning of species can have important consequences (Flickinger et al., 1980). Pesticides may also have indirect consequences of birds and mammals populations as they affect negatively their habitats.

- Negative impact on soil regeneration. Some pesticides are toxic to several organisms in the soil (worms, fungi, bacteria, etc.). These organisms regenerate the quality of the soil, deteriorate and recycle green waste, and allow nitrogen to be fixed on the crops.

Greenhouse gas emissions due to production and spread of pesticides should be added to the analysis of Pimentel, but they have been reviewed in the previous susbection. The environmental consequences of herbicides are similar to those of pesticides and the same typology is still relevant. The environmental consequences of fertilizers appear to be more simple to analyze, because most of the environmental externality of fertilizers application comes from green house gas released (Tubiello et al., 2014).

The impact of herbicide tolerant crops on herbicide application has been rather heterogenous, with reductions of total application in some countries and increases in others (Qaim, 2009). For instance, Benbrook (2012) estimated that they have led to a significant increase in herbicide use in the US over the 1996-2011. However, even when the adoption of herbicide tolerant crops cause an increase in total herbicide use, the herbicides that are spread over these crops (essentially glyphosate or glufosinate) appear to be less harmful to famers' health and the environment than the mix of herbicides it replaced (Demont et al., 2004). As stated by Märländer and Bückmann (1999): "both herbicides [glyphosate and glufosinate] have a low toxicity and are metabolized fast and without residues in the soil". In some cases, the increase in herbicide use can be even favorable to the environment, as in Canada where most species of weed flora is actually imported invasive varieties which destruction is positive for genuine flora (Lutman and Berry, 2006). The case of pest resistant crops is more homogenous qualitatively: everywhere it has been adopted, it reduced the use of pesticides (it did not eliminate fully pesticides, however, because *Bt* is quite specific to some pests and does not control others) and increased yields (Qaim, 2009, Table 1). Some quantitative heterogeneity lies, however, in the relative magnitude of the yields and pesticide level effects. Where farmers used low levels of pesticides (relatively to pest pressure), the yield effect dominates following the introduction the introduction of *Bt* crops: farmers will not use significantly less pesticides, but their output per acre will increase significantly. This is quite intuitive: if farmers use low levels of pesticides, it is quite likely that a lot of output is lost because of low control of pests, in particular those that are sensitive to *Bt*. Hence, the introduction of pest resistant crops will offset these losses, but it will still be quite profitable for farmers to apply roughly the same quantities of pesticides. Reciprocally, if the farmers apply a lot of pesticides, pests are likely to be well controlled, and the introduction of *Bt* crops will improve pests control only, but will not increase yields. However, some of the applied pesticides will become unnecessary. In addition to the general decrease in pesticides spread following *Bt* crops adoption, the decrease was mainly focused on most toxic insecticides (Qaim, 2009, Fig. 4). The positive impact of reduced chemicals use on the environment (including on public health off-farm) comes along with improvement of the farmers health, through reduced exposures to these products. This is particularly true in developing countries, where relevant prevention procedures against negative chemical consequences are less widespread among farmers.

3.4 Agricultural R&D and land use

Beyond its biodiversity effects, cultivated land extension has several other environmental impacts: greenhouse gaz emissions (Wise et al., 2009), contamination of on-farm land by chemical use, etc. Peace Nobel Prize winner[15] Norman Borlaug (2002) hypothesized that the improvement of agricultural varieties allowed, through land sparing, to avoid important surfaces to be converted to agriculture. This optimistic vision of agricultural innovation role in limiting land use is referred to as the "Borlaug's hypothesis" (Angelsen and Kaimowitz, 2001), and has been challenged by several authors who imagined that, on the contrary, enhanced productivity in agriculture may exemplify Jevons's paradox (Rudel et al., 2009; Lambin and Meyfroidt, 2011). In 1865, William Jevons had observed that despite improvement of James Watt steam engine throughout the 19th century, the consumption of coal increased simultaneously (Jevons, 1865).[16] The idea that increasing productivity releases land is actually based on the hypothesis that agricultural output is kept constant during the innovation adoption process. Under such hypothesis (*i.e.* comparing land used to produce actual output with land required to produce the same output with 1966 yields), Waggoner (1996, Figure 1) estimates that around 60 millions of hectares have been spared in India in 1992. Yet, this assumption is unrealistic. Borlaug's statement that "had 1961 yields still prevailed today, three times more land in China and the USA and two times more land in India would be needed to equal 1992 cereal production" (Borlaug, 2002). One may object that if the yields of 1961 still prevailed in 1992, the total cereal production would most probably not be equal to what has been actually observed. The extension of cultivated surfaces has several important environmental consequences: modification of wildlife habitat reshaping biodiversity (Green et al., 2005; Fischer et al., 2008), greenhouse gaz emissions from land use

[15]For his works on wheat varieties in the early 1960s, that allowed to triple wheat yields and made him the "father of Green Revolution", Norman Borlaug was granted Peace Nobel Prize in 1970.

[16]Technological improvement of the steam engine allowed a decrease in engine work prices that made it profitable to extend the use of steam engines to activities in which it was not profitably operated before. Overall, this extension of steam engines more than offset the impact of efficiency gains on coal consumption where the steam engined was deployed before innovation.

conversion (Wise et al., 2009), deforestation (Villoria et al., 2014), extension of areas contaminated by chemicals, etc. According to Gibbs et al. (2010), most of the 1980s-1990s deforestation was due to agriculture expansion. The relation between agricultural R&D (more specifically of its major outcome, productivity) and land use is, hence, a crucial aspect of environmental impact of agricultural R&D.

Several papers have studied the impact of technological progress on agriculture extension, both empirically and theoretically. Intuitively, Jevons's paradox is the result of opposing forces on both supply and demand side, some reducing, others increasing land use. If an innovation increases land productivity, assuming prices remain constant, it will make land relatively cheaper and turn profitable land plots that, initially, were not (Barrows et al., 2013), expanding cultivated area. However, except if output demand is perfectly elastic, assuming constant output, competition among farmers will result in lower prices, and will, finally, make agriculture expansion less profitable and thus reduce cultivated area. In the end, if demand is sufficiently elastic, the reduction in price will increase demand for output, and, consequently, cultivated area. The overall balance of these forces in the general case is not clear *a priori*, and a case-by-case approach is necessary.

Hertel (2012) provided a complete theoretical discussion of the conditions under which the Jevons's paradox or the Borlaug hypothesis dominates the other one. Hertel considered the production of an agricultural commodity in a rather simple model of partial equilibrium. Farms produce the commodity using land and other "non-land" inputs, and sell their output on a perfectly competitive market (in particular, under a zero profit condition). The price elasticity of demand for agricultural input is constant. The prices of all inputs except land are constant and exogenous, and the price elasticity of land supply is assumed to be constant. Hertel examined two possible types of innovation, first available uniformly in a given region: a *Hicks-neutral* innovation (*i.e.* a uniform increase in productivity of all inputs) and a *land-biased* innovation (*i.e.* an increase in land productivity only). In this model, innovation's effect on land use should be decomposed into two "sub-effects": one on the yield of land (producers adjust the mix of non-land inputs to modify production per unit of land), referred to as the *intensive margin* effect; and one on the extension of cultivated land, the *extensive margin*. The price elasticity of output supply, ε_S has then an extensive[17] and an intensive[18] components. When innovation is Hicks-neutral, innovation reduces land use if and only if price elasticity of demand is lower than 1 - which corresponds to the implicit assumption of the Borlaug's hypothesis that output remains roughly constant despite innovation. When land biased innovation is considered, in addition to demand price elasticity, other parameters have to be taken into account to discuss the impact of innovation on land use. Of course, elasticity of demand remains a crucial parameter, and Jevons's paradox is all the more likely as demand is elastic. But another relevant parameter is the elasticity of substitution between land and non-land inputs: more substitutable factors make Jevon's paradox more likely to occur.[19] Finally, the share of land in total production costs matters as well, although its effect on the likelihood of a Jevons's paradox depends on the other parameters. A single region analysis may miss some interesting effects, as a Jevons's paradox on one market may be either compensated or exacerbated by land use change on another region. Thus, Hertel extended his model to two regions, one able to use a Hicks-neutral innovation, and the other one unable to do so. The model did not yields general necessary nor sufficient conditions for Jevons's paradox to arise or Borlaug's hypothesis to be verified, but provided results on the likelihood of each of these situations. By analogy to the single region case, an elastic *excess* demand in the region where innovation occurs is a necessary condition[20] for Jevons's paradox to occur. However, when it is the case, the elasticity of global demand for land with respect to total factors productivity is lower than in the single region model: as noted by Villoria et al. (2014), "the inelastic nature of global food markets is likely to induce 'leakage' effects via trade". Finally, it is quite likely that innovation and productivity gains on the agricultural commodity market will trigger changes on other markets: higher wages on the labour market and returns on the

[17]The extensive component is $\varepsilon_i^s = \varepsilon_L/\theta_L$ where ε_L is the exogenous price-elasticity of agricultural land supply and θ_L is the share of land in the total production costs. As noted by Villoria et al. (2014), public policy can influence ε_L through land property rights regime: if the public policy defines a certain surface to be dedicated to agriculture, $\epsilon_L = 0$.

[18]The intensive component is $\varepsilon_e^s = \sigma\left(\theta_L^{-1} - 1\right)$ where σ is the (constant) elasticity of substitution between land and non-land inputs.

[19]This point is quite intuitive. Imagine that substitution between inputs is impossible and a land biased innovation is discovered, increasing productivity of land. Depending on output demand elasticity, demand for land will either increase or decrease, but productivity increases will "remain" in demand for land. Suppose now that substitution is possible. Since farmers can modify their input mix and, due to innovation, land becomes relatively more productive than non-land inputs, it will be profitable for farmers to rebalance their input mix towards land, increasing their land use.

[20]This is, $\varepsilon_D^A > 1$, with ε_D^A the price elasticity of *excess* demand in the region that adopts the innovation.

capital market, changes in consumption behaviors, etc. These general equilibrium effects are not captured by partial equilibrium models (Villoria et al., 2014), and they probably make Jevons's paradox slightly more likely to occur.

A very interesting argument of Hertel (that can be linked with empirical observation, cf *infra*) is that the land-use outcome of an innovation is likely to depend significantly on the scale at which it is adopted. Locally, it is quite probable that demand is almost perfectly elastic (output prices are almost constant, equal to international market prices, thus innovation will probably not have impact on prices), while on a broader scale, demand is more rigid and prices are more likely to evolve with the introduction of the innovation. Hence if an innovation is adopted on a small scale and studied at the same scale, it will more probably result in an expansion of cultivated surfaces, which is less probable with a widespread innovation at a more global level of analysis.

Villoria et al. (2014) provided a review of empirical works and simulations trying to clear the Borlaug/Jevons debate in the specific case of deforestation (*i.e.* considering extension of cultivated surfaces at forest frontiers only)[21], distinguishing cross-country, country and local level studies. Results surveyed at the local scale are quite mixed. First, in cultivated areas away from forest frontier, existing studies do not highlight any definitive answer to this issue (Jayasuria, 2001; Shively and Pagiola, 2004; Maertens et al., 2006). Second, at the forest frontier, results are mixed as well. On the one hand, Fisher and Shively (2007) found that innovation tends to reduce deforestation. On the other hand however, Yanggen and Reardon (2001) found evidence of the contrary. At the country wide level, available studies (Foster and Rosenzweig, 2003; Garrett et al., 2013) concluded that technological progress in agriculture (in India and Brazil, respectively) has led to expansion of cultivated land. At a global scale, Ewers et al. (2009) and Rudel et al. (2009) studied the impact of agricultural yields increases on land use. Although the effects identified by these studies are small and not very significant, and although, in some particular regions or periods of time[22], the Borlaug's hypotheses may have been verified, they found that, overall, Jevons's paradox has been more likely.[23] However, as pointed

[21]Most empirical works focus on forest frontiers, mainly because more reliable data is available about this issue - conversion of forests to agricultural land and *vice versa* being easier to observe than conversion from grassland to cultivated surface, for instance.

[22]For instance, between 1980 and 1985, globally, agricultural yields have increased while cultivated areas have decreased significantly (Rudel et al., 2009, Fig. 1).

[23]In addition, Ewers et al. (2009) found a weak evidence that land sparing innovation is more

out by Villoria et al. (2014), these studies suffered from weaknesses in the econometric strategy. In particular, first, yields may be a poor proxy for innovation (as shown by Hertel, yields increase can result from inputs substitution as much as innovation). Second, at least at a global level, yield increases are likely to be partially caused by increases in cultivated surfaces.

The effect of agricultural R&D on the environment through land use is thus not clear cut. Although the mechanisms at stake in the forces in favor of the Jevons's and Borlaug's point of view are quite intuitive, the available empirical evidence is hardly convincing. A possibility is that one of the theories only is verified in a given context, in which case the mixed empirical results are flawed. Another, more probable option is that the actual effect of innovation on land use is a more complex combination of extension and land-sparing, that would deserve further, case-by-case analysis.

3.5 Coexistence of newly developed crops and other organisms

Another much debated environmental effect of new varieties, especially GM crops (although it is equally relevant for conventionally bred varieties), is their impact on non-target organisms, and on other relative plants. Various issues are potentially caused by coexistence of new crops and other organisms: destruction of biodiversity, contamination of organic cultures by non-organic genes, diffusion of stronger weeds, etc.

Impact on non-target crops can be subdivided into two categories: direct effect on non-targeted organisms (which is relevant for insect resistant crops only), and indirect effects on predators of targeted pests and parasitoids (Lutman and Berry, 2006). The most mediatized example of direct effect on non-targeted has been the lethal power of *Bt* trait over the Monarch butterfly that has been revealed by Losey et al. (1999). Mitigating the results of Losey et al., Stanley-Horn et al. (2001) showed a more complex reality. The monarch larvae appear to be sensitive to exposure to

likely to arise in developing countries, where agricultural subsidies are supposed to be lower. They also found that innovation reduces cultivated surfaces more often when the agricultural market does not face supply shortage. This last result somehow contradicts the result of Hertel's model, because elasticity of demand is larger when there is no shortage than when consumers hardly find enough food (a shortage is most likely to imply an inelastic demand).

high concentrations of *Bt* (much higher than the doses observed on fields of GM *Bt* crops), no significant effects appear on the survival rates of adult butterflies. The risk of direct destruction thus seems negligible before other on-field threats to this butterfly - in particular, the usual treatment, on non *Bt* fields, with λ-cyhalothrin. Anyhow, the risk exists and deserves a case-by-case study for each variety - which is undertaken by most regulators. According to a review of laboratory and field work that studied this side effect of GM crops by Lutman and Berry (2006, p. 268), the threat of indirect effect on natural predators of targeted pests is more pregnant. It is thus, undoubtedly, a negative environment side effect of innovation on varieties. Another indirect effet of innovation on other organisms is the impact of change in farming practices induced by herbicide tolerant varieties. In particular, they have caused a switch in herbicide mix and a wider adoption of conservation tillage practices. This has been studied in section 3.3.

Improved genes (either by genetical engineering or by conventional breeding) of a given crop may also “flow” to related varieties. Different types of such gene flow should be examined. First, genes can flow from the new crop to one of its wild relatives. However, Lutman and Berry (2006) consider that the wide development of GM weeds because of gene flow is very unlikely for several reasons. The presence of sympatric[24] weeds geographically close to the cultivations is rare. Moreover, if some genes flow to weeds, hybrid offspring of these weeds is unlikely to be fertile. Even if in this unlikely case, it is quite probable that the fertile offspring will not be resistant enough to propagate (cultivated varieties are very fragile, and particularly not adapted to grow in wild nature - a hybrid from a weed and a cultivated variety is quite likely inherit its fragility). Second, gene flow is much more likely to occur among crops, *e.g.* from a GM to a non-GM variety of the same crop. It has always happened between conventionally-bred varieties, and happens similarly between GM and conventional crops. Numerous papers have studied the shape of the relation between distance and gene flow between two fields (Beckie et al., 2003; Eastham et al., 2002), and conclude that, in order to avoid gene flow, spatial separation is the most effective technique. However, such strategy never guarantees a strict absence of the flow phenomenon.

In the long term, the flow of gene is all the more potentially annoying that the

[24]The sympatric plants of a given species are those that can actually by fecundated by this species.

genes that are transferred to relatives provide strong resistance to the offspring (if the offspring of "contaminated" varieties are not particularly strong and resistant, the gene flow's consequences will be limited to the next generation only, and its overall effect will thus be marginal). Although invasive species are rarely cultivated crops but are more often weeds (Lutman and Berry, 2006), it may be that some of the recently developed traits provide crops with particular resistance, even away from a cultivation context. In particular, *Bt* and drought resistance traits, that have been developed by genetical engineering, strengthen their holders even without human intervention. For instance, Snow et al. (2003) have shown that transferring sunflower *Bt* genes to wild sunflower make the latter more resistant to being eaten by insects, and hence increase their production of seeds. Similarly, there is a weak likelihood that herbicide tolerant varieties become invasive, or that a flow of herbicide tolerance traits to wild relatives have negative environmental consequences.

Overall, the question of undesired gene flow from improved varieties to previously existing one is a serious threat of crops R&D on the environment. This issue has been much debated in the context of GM crops, but it should be underlined that it concerns conventionally bred innovation to the same extent. Empirical results are still scarce and discussed, and this dimension of environmental effect of innovation on crops is one of the most poorly understood.

3.6 Innovation and resistance

Whenever a new variety (or a new herbicide/pesticide) is developed to be less sensitive to existing damages from living organisms, nature (*i.e.* pests and weeds), an adaptation process starts. Laxminarayan (2003) termed this process *adaptive destruction*. The Insecticide Resistance Action Committee defines resistance as "a heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that pest species". This phenomenon causes any bio-innovation (beyond agricultural biotechnologies, adaptation happens with pharmaceutical ones as well) to be rendered obsolete, even if no more efficient substitute is developed afterwards. The adaptive destruction process is a mere result of the fact that the innovation disproportionately selects the pests and weeds that can overcome the specific advantage of the innovation (Laxminarayan, 2003).

Every actor of agricultural production benefits from the prevention of adaptation and should be involved in it. Farmers obviously benefit from adaptation management, because adaptation makes pests more difficult to control. Innovators benefit from it as well, because adaptation reduces the market value of their product and, hence, the rent they can capture. Finally, the fight against adaptation is a public good (it is profitable for any farmer not to take mitigation measures and rely on others to undertake prevention), so society benefits from the prevention of adaptation. However, few preventive actions against adaptation have been undertaken in the past, and the few ones have been rather individual and lacked coordination. The case of adaptation to *Bt* crops, on the contrary, has benefited from a series of measures, coordinated by environment regulators, involving all the relevant actors.

After the first commercialization of *Bt* crops in 1996, a first case of pest resistance was documented in Gujarat (India) in 2007, and since then resistance occurence has spread in different parts of the world. To mitigate the diffusion of resistance, seed producers, farmers and regulators have worked together to define a coordinated strategy. In the United States, the resistance management strategy developed by the US Environmental Protection Agency (US EPA) is named Integrated Pest Management. It aims to prevent and fight resistance to *Bt*. It is derived from a high-dose/refuge strategy, imposing that *Bt* crops produces a high level of toxin and that farmers dedicate at least 20% of cultivated area to non-*Bt* cultures. This strategy relies on the assumption that the allele coding pest resistance is recessive. In that case, whenever a resistant pest (which, under this assumption, is necessarily homozygote) reproduce with a non resistant one, their offspring is quite likely not to be resistant.[25] This element justifies the refuges, in order to ensure that there are as many non resistant pests as possible around the *Bt* field to reproduce with resistant pests. However, it is also important to destroy as much as possible the non resistant heterozygote pests because their offspring with resistant pests have a non-zero probability to be resistant.[26] This is the role of the high dose of *Bt* constraint. In addition, the US EPA also mandates to farmers that they plant "pyramidal" *Bt crops* (*i.e.* crops with stacked genes, emitting different types of *Bt* toxins that are active against the targeted pest). The justification of this rule is

[25] In a very simplified model where one gene only codes resistance, the offspring of a resistant and a non resistant pest is non resistant with probability 1 if the non resistant parent pest is homozygote, and probability 0.5 if it is heterozygote.

[26] In the simple model of previous footnote, the resistance of the offspring from a resistant and a non resistant heterozygote pest occurred with probability 0.5.

that if a pest is resistant to one *Bt* toxin, it is extremely unlikely that it will have developed resistance to many of them. All this reasoning does not apply in the case resistance is dominant, but Tabashnik et al. (2013) explained that, in such adverse situation, the refuge strategy is able to delay significantly the spread of resistance. Finally, comparing data from 77 studies published before 2012, Tabashnik et al. (2013) showed that the prediction of pyramid theory (namely that when resistance is recessive and pyramidal *Bt* crops are planted, the high-dose/refuge strategy makes the development of resistance significantly slower) is verified in field trials.

Resistance issues also arise concerning herbicide tolerant crops. Resistance to glyphosate is a crucial problem for farmers and research firms. According to Brookes and Barfoot (2014), 28 species of weeds had developed glyphosate resistance in 2014 worldwide. In reaction to adaptation, farmers are advised to include other herbicides in their treatments of weeds. As a consequence of such phenomenon of weeds adaptation, the gain in herbicides highlighted in section 3.3 toxicity may well prove only transitory in the long term. Indeed, between 2006 and 2012, the share of GM herbicide tolerant crops receiving treatment from other herbicide than glyphosate increased from 14% to 59%.

The environmental impacts of R&D on varieties are thus a complex mix of positive and negative effects, on different dimensions of what is referred to as "environmental impacts". On some of these dimensions, the impact of crops innovation is considered as positive by a fairly wide consensus. This is the case, for instance, for the footprint of chemical use, that has been reduced by new generations of crops, especially GM crops and, in particular, *Bt* ones. On some other dimensions, it is difficult to draw a general balance, because the actual environmental impact of crops R&D depends on several other factors. This is the case, for instance, for the effect of innovation on biodiversity conservation through land use variation, which depends on the structure of each market and production system. Finally, the actual effect of crops innovation on other dimensions of the environment are simply not documented enough to be clearly considered as positive or negative. However, if they are negative, the actual consequences would be very serious, and innovation should thus be managed accounting for this uncertainty. This the case, for instance, for the possible gene flow of improved traits. Whether the overall impact of R&D on varieties is positive or negative thus depends on the importance granted to the different dimensions of the environment, and to the social preferences regarding uncertainty.

Chapter 2

May innovation on varieties share agricultural land with nature, or spare land for it?

Abstract

The development of new, more productive varieties has been at the core of the transformations of agriculture throughout the 20^{th} century, and of its environmental impacts. Among the various environmental effects of agriculture, the ability to choose between a wide, low-intensity agriculture, and a concentrated, high-intensity one, is a crucial component of its impact on biodiversity conservation. The impact of innovation on land use and intensity of agriculture is thus an important determinant of such innovation's environmental footprint. The existing literature has studied how innovation modifies land use, but has not focused on how it changes production intensity. The objective of this paper is to complement the existing analytical framework to account for the impact of varieties improvements on non-land inputs. We show that innovation can simultaneously reduce land use and increase agricultural intensity only if it is biased towards one of these production factors.

1 Literature review and motivation

The environmental impact of agriculture has been acknowledged, for a few decades, as a major concern (Lichtenberg, 2002). While farmers ensure stewardship of their environment and thus provide positive externalities (*e.g.* maintaining hedgerows, providing scenery), agriculture also contributes to several environmental problems (*e.g.* chemicals runoff, salinization of rivers, etc.). One of the most striking features of the agricultural production system throughout the 20th century has been a sharp increase in productivity, in which technological progress has played a major role (Pardey et al., 2014). The impact of technological progress on the depletion of environmental quality as a consequence of agricultural production is thus quite likely to be important, but it has been largely, and is still, debated (Qaim, 2009; Qaim and Klümper, 2014). Some authors have suggested that improved inputs have made environmental quality less of a concern for production, reducing incentives for farmers to steward the environment (Strange, 1988). Others have suggested that innovation provides more efficient technologies that mitigate agriculture's environmental impact (Khanna and Zilberman, 1997).

Biodiversity bears a large share of the negative consequences of agriculture on the environment. Conversion of forests, wetlands and grassland into agricultural surfaces has caused considerable habitat losses, especially in tropical areas (Fearnside, 2005; Nepstad et al., 2008; Gibbs et al., 2010). Moreover, such conversion causes greenhouse gaz emissions and hence strengthens the impact of climate change on habitats and species (Phalan et al., 2013). The stronger reliance on chemicals has depleted soil biota and insect populations (Matson et al., 1997). In particular, the widespread rise of pesticides has caused the destruction of large populations of bees and pests which were natural ennemies on farm, and have drifted in surrounding lands and water streams, killing fish and other wildlife (Pimentel et al., 1991, 1993). The intensity and extent of production lie at the core of agricultural externalities on biodiversity. An important literature in ecology has focused on this issue, from the *land sharing/land sparing* debate point of view (Cassman, 1999; Trewavas, 2001; Green et al., 2005; Vandermeer and Perfecto, 2007; Fischer et al., 2008). Such debates focuse on the optimal tuning, in order to produce *a given level of agricultural output*, between wide, low intensity (land sharing) and concentrated, highly intensive cultures allowing to save some land free of any agricultural production (land sparing).

In the land sharing/land sparing model, such optimum depends on the shape of the relationship between intensity of agriculture and species density. A growing share of literature has tried to empirically evaluate this relationship (Phalan et al., 2014). Its shape depends strongly on the area and species considered. For instance, Phalan et al. (2011) found biodiversity to be a convex function of agricultural intensity for the bird species and trees they studied in Ghana and India. These species require almost intact habitat to be conserved, and even a very cautious, low intensity agriculture has a strong detrimental effect on them. A convex relationship advocates for a land sparing strategy, while a concave relationship calls for more land sharing. Indeed, if this relationship is convex, a lot of species are lost in the low levels of intensity but the marginal effect of intensity on the species decreases rather rapidly. Spreading intensity uniformly over the available surfaces would thus cause important species losses, and it is more sensible to sacrifice almost all species on a limited piece of land, because it allows to save all species on the remaining uncultivated surface. Reciprocally, if the relationship is concave, the marginal effect of intensity on losses of species becomes really significant for high intensity only, and it is thus sensible to avoid largely intensive cultures as much as possible. The possibility to opt for land sparing, however, relies heavily on the possibility to intensify cultures, which "remains a major target of research and development" (Matson et al., 1997). In order to meet global food needs in the future, several options are acknowledged to have positive effects on the environment (Chappell and LaValle, 2011): improving nutritive quality of commodities, reducing waste (Hodges et al., 2011), turning to less demanding diets (Meier and Christen, 2013). However, it is likely that achieving such goal will rely, at least partially, on increasing total agricultural output as well (Borlaug, 2002; Tilman et al., 2011). Whether this can be done mitigating agriculture's footprint on the environment in general, and on biodiversity in particular, remains a crucial issue (Tilman et al., 2011).

Globally, agriculture surface has significantly expanded since the middle of the 20^{th} century, although with large disparities across countries. Across the world, arable and total agricultural land, respectively, increased from 9.8% and 34% of global land in 1961 to 10.8% and 37.7% in 1993, and remained roughly constant since then (FAO, 2016). Several authors have argued that the large increase in agricultural productivity, as a result of agricultural R&D effort since the 1930s, has been crucial in containing the increase in land use (Waggoner, 1995; Borlaug, 2002). This idea that productivity gains have allowed to save land for other uses than agriculture has been referred to as the *Borlaug hypothesis* (Hertel, 2012). Further, some have stated that if yield growth slows down in the future, the impact on land use will be strongly negative, *i.e.* will increase significantly arable surfaces (Wise et al., 2009). However, although such idea that innovation is always land sparing is straightforward for a given agricultural output, it is easily challenged by a broader market equilibrium, in which total output evolves with productivity gains and demand fluctuations. Indeed, more productive varieties make cultivated land more profitable, which increases production at the extensive margin (Barrows et al., 2013): some land that was not profitably cultivated with the existing varieties turns out to be profitable when planted with the new varieties. Such mechanism is often referred to as the Jevons paradox. The extension of cultivated surface will, in turn, increase the total agricultural output, which is likely to decrease the commodity prices, and reduce the profitability of land extension. The relative magnitudes of the extensive margin and demand effects depend on supply and demand behaviors, making the overall impact of innovation on agriculture land use uncertain. Hertel (2012) develops a theoretical general equilibrium model to analyse the effect of innovation on land use. He finds that demand price-elasticity plays a crucial role in the land-use impact of agricultural innovation: an elastic demand makes the Jevons paradox more likely to arise.

There is remarkably scarce empirical evidence to inform the Borlaug/Jevons debate in the case of agricultural production. Villoria et al. (2014) provide a review of such works in the specific case of deforestation (*i.e.* considering extension of cultivated surfaces over forests only)[1], distinguishing cross-country, country and local level studies. Results surveyed at the local scale are quite mixed. Studies focussing on innovations adopted in cultivated areas away from forest frontier (Jayasuria, 2001; Shively and Pagiola, 2004; Maertens et al., 2006) and a study focusing on innovation adoption at the forest frontier (Fisher and Shively, 2007) found that the kind of innovation adopted there tended to reduce deforestation. However, Yanggen and Reardon (2001), studying the forest frontier, found evidence of the contrary. At the country wide level, Foster and Rosenzweig (2003) and Garrett et al. (2013) concluded that technological progress in agriculture (in India and Brazil, respectively) has led to expansion of cultivated land. At a global scale, studies by Ewers et al.

[1]Most empirical works focus on forest frontiers, mainly because more reliable data is available about this issue - conversion of forests to agricultural land and *vice versa* being easier to observe than conversion from grassland to cultivated surface, for instance.

(2009) and Rudel et al. (2009) studied the impact of agricultural yield increases on land use. The effects (either supporting the Borlaug's hypothesis or the Jevons's paradox) identified by these studies are small and not very significant. Moreover, the Borlaug's hypothesis has been verified in some particular regions or periods of time.[2] However, the studies reviewed previously tended to support the idea that, overall, the Jevons's paradox has been more likely to occur than the Borlaug's hypothesis.[3] Nevertheless, as pointed out by Villoria et al. (2014), these studies suffered from weaknesses in the econometric strategy. In particular, two flaws should be underlined. First, yields may be a poor proxy for innovation (as shown by Hertel, yields increase can result from inputs substitution as much as innovation). Second, the econometric strategy probably suffers from endogeneity, because, at least at a global level, yield increases are likely to be partially caused by increases in cultivated surfaces.[4]

In addition, in these empirical studies about the impact of innovation on varieties on land use, innovation is treated as a homogenous and integrated process, and the different types of innovations are not taken into account. Yet, different types of innovation have been discovered throughout the history of agriculture, and in particular in the last century (Beddow et al., 2009). Some of these innovations have increased the total productivity of factors, and some have made some inputs (herbicides, pesticides, etc.) more productive than they used to be. Such heterogeneity may also explain, to some extent, the mixed results obtained by the empirical literature. If this has been the case, taking into account the type of innovation in empirical studies may improve the significance of the results.

Finally, whether technological innovation actually reduces the agricultural land use is not sufficient to conclude about its land sparing effects. Indeed, it is still possible that innovation will cause cultivated surfaces to increase and the use of inputs to be more intense simultaneously, which would not be of any kind of land sharing. This is what we intend to study in this paper. We use a simplified ver-

[2]For instance, between 1980 and 1985, globally, agricultural yields have increased while cultivated areas have decreased significantly (Rudel et al., 2009, Fig. 1).

[3]In addition, Ewers et al. (2009) found a weak evidence that land sparing innovation is more likely to arise in developing countries, where agricultural subsidies are supposed to be lower, and when the agricultural market does not face supply shortage. This last result contradicts the result of Hertel's model - as before a shortage, demand for food is quite likely to be inelastic.

[4]For example, increased cultivated surfaces improve the revenue of firms, including R&D ones, which, in turn, increase the funds available to conduct research for further yield increases.

sion of the model developed by Hertel (2012) to compute the impact of improved agricultural varieties on both land and inputs use, simultaneously. We choose to focus on the major types of genetically engineered (GE) crops: herbicide tolerant, insect resistant and drought resistant varieties. Herbicide tolerant (HT) crops allow farmers to spray some particular herbicide (glyphosate for *Roundup-ready* crops or glufosinate for *LibertyLink* ones) over their fields without having to target weeds only. Insect resistant (IR) crops produce a pesticide, *Bacillus thuringiensis* (*Bt*), without farmer's intervention. Finally, drought tolerant crops require particularly low quantities of irrigation to grow vigorously. Our study shows that for innovation to drive land sparing under market conditions, rather strong hypotheses should be verified, and these hypotheses depend on the type of innovation. Land sparing may only partially arise if innovation is Hicks neutral. Land biased and pesticides biased innovations may be fully land sparing if demand is sufficiently inelastic and factors sufficiently hardly substitutable.

2 The model

As in Hertel (2012), assume that a quantity y of an agricultural commodity is produced by a farmer using two inputs, land and pesticides (the quantity per acre of other inputs, such as seeds, fertilizers, etc. are taken as constant and exogenously defined). The output price is p_y, and the farmers produce the commodity under a zero profit constraint. The variables relative to land and pesticides are denoted with a subscript l and p respectively. Denote x_i and p_i the respective quantity and price of input $i \in \{l, p\}$ used by the farmer. Assume a constant elasticity of substitution production function, of elasticity $\sigma > 0$ and total factor productivity α. The marginal productivity of factor $i \in \{l, p\}$ is a_i. Define θ_i as the share of input i in production costs:[5]

$$\theta_i = \frac{p_i x_i}{p_l x_l + p_p x_p} \tag{2.1}$$

Denote $\hat{z}$ the relative variation of variable z ($\hat{z} = dz/z$), and the market equilibrium is defined by the following set of equations:

$$\hat{x_l} + \hat{a_l} = \hat{y} - \hat{\alpha} + \sigma\left[\hat{\alpha} + \hat{p_y} + \hat{a_l} - \hat{p_l}\right] \tag{2.2}$$

[5]Details of calculations can be found in appendix.

$$\hat{x_p} + \hat{a_p} = \hat{y} - \hat{\alpha} + \sigma \left[\hat{\alpha} + \hat{p_y} + \hat{a_p} - \hat{p_p}\right] \tag{2.3}$$

$$\hat{\alpha} + \hat{p_y} = \theta_l \left(\hat{p_l} - \hat{a_l}\right) + \theta_p \left(\hat{p_p} - \hat{a_p}\right) \tag{2.4}$$

The demand for inputs is described by (2.2) and (2.3) while (2.4) results from the zero profit condition. In addition, suppose a constant price-elasticity demand function $y = p_y^{-\varepsilon_d}$, and exogenous constant prices for all inputs except for land, which is assumed to be supplied with a constant price-elasticity $x_l = p_l^{\varepsilon_l}$. Then, the previous set of equations can be written as:

$$\hat{x_p} = (\sigma - 1)\left(\hat{a_p} - \hat{a_l}\right) + \left(1 + \frac{\sigma}{\varepsilon_l}\right)\hat{x_l} \tag{2.5}$$

$$\hat{x_l} = \hat{y} + (\sigma - 1)\hat{\alpha} + (\sigma - 1)\,\hat{a_l} - \sigma\left(\frac{\hat{y}}{\varepsilon_d} + \frac{\hat{x_l}}{\varepsilon_l}\right) \tag{2.6}$$

$$\hat{\alpha} - \frac{\hat{y}}{\varepsilon_d} = \theta_l\left(\frac{\hat{x_l}}{\varepsilon_l} - \hat{a_l}\right) - \theta_p\hat{a_p} \tag{2.7}$$

In any case examined below, the improvement of agricultural varieties increase the total commodity output.

2.1 Herbicide tolerant varieties

We first focus on the case of herbicide tolerant varieties. Such type of genetically engineered crops are *Hicks neutral*: they are likely to increase total factor productivity.[6] Indeed, they do not make one factor more efficient asymmetrically, and, in our model, increase indifferently the productivity of all factors. Hence, suppose the improvement of such varieties can be represented by $\hat{\alpha} > 0$, $\hat{a_p} = \hat{a_l} = 0$. Then, the following proposition holds:

Proposition 1: Improving herbicide tolerant varieties reduces simultaneously land and pesticides use if and only if demand is inelastic ($\varepsilon_d < 1$).

The proof of this proposition is in appendix. The expression for the variations

[6]The increase the marginal productivity of herbicides, because the application of herbicides the plant are resistant to is much easier than the application of low-dose herbicides on conventional varieties. They also increase the marginal productivity of land, because the herbicides that can be spread have a lower toxicity (Demont et al., 2004), and allow to reduce tillage practices (Brookes and Barfoot, 2014), which mitigates soils depletion.

in land and pesticides use are given by:

$$\hat{x_l} = \frac{\varepsilon_l\left(\varepsilon_d - 1\right)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{\alpha} \tag{2.8}$$

$$\hat{x_p} = \frac{\left(\varepsilon_l + \sigma\right)\left(\varepsilon_d - 1\right)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{\alpha} \tag{2.9}$$

A similar reasoning to the one developed on land in introduction actually applies to the use of pesticides: the CES function assumes decreasing marginal returns of pesticides, as it does for land. Hence, at the extensive margin, the innovation makes it profitable the use of more pesticide: if innovation encourage farmers to increase their production at the extensive margin, land and pesticides use will increase simultaneously. Because innovation is Hicks neutral, the substitutability of factors (σ) and price elasticity of land supply are not crucial determinants of change in land and pesticide change. They do not influence the direction of the variation of production factors use. Indeed, if innovation increases the productivity of all factors, farmers will not endeavor to substitute one factor to the other, and use more of the latter and less of the latter.

The magnitude of the effect, however, depend on the values of the elasticities. Suppose innovation increases the use of factors ($\varepsilon_d \geq 1$). We show in appendix that the increase in land use is all the smaller, and the increase in pesticides use is all the larger that factors are substitutable. This means that, although the productivity of both factors increase with innovation, the farmers are seeking to substitute pesticides to land: if factors are easily substitutable, the farmers will rely more on pesticides than on land to produce more output. Moreover, we show that the increase in land use is all the larger that elasticity of supply of land. Indeed, a larger elasticity of land supply makes it less expensive to extend cultivated surface for farmers (or makes it less profitable to reduce it). The effect of elasticity of land supply on the use of pesticides is more ambiguous.[7]

In the case of Hicks neutral innovation, the elasticity of demand is the only

[7]It is probably more intuitive to understand the mechanism by considering a decrease in elasticity of land use. This makes it more expensive for farmers to increase their use of land. Hence, they will seek, as much as possible, to substitute pesticides to land. Hence, if substitution is easy enough, a decrease in elasticity of land supply will strengthen the increase in the use of pesticides following innovation. So, if the elasticity of substitution of factors is large enough, an increase in elasticity of land supply will weaken the increase in pesticide use, because farmers will aim to rely more on land than on pesticides to increase their production.

parameter to have an influence on the direction of the change in inputs use. If the demand is very elastic, then the price of the commodity depends weakly on the quantity of output produced by the farmers, even when the innovation is discovered. Hence, almost only the extensive margin effect occurs, and the cultivated surfaces extend and quantities of pesticides increase. Reciprocally, if the demand is perfectly inelastic, $\varepsilon_d = 0$, the total output does not vary at all, which is precisely the condition of the Borlaug hypothesis. In this case, the use of land and pesticides decreases with innovation. A Hicks-neutral innovation, such as improvement of herbicide tolerant varieties, will thus spare some land for biodiversity if, and only if, demand is sufficiently inelastic. Actually, in that case, it will simultaneously share land with nature, because farmers will reduce culture intensification.

2.2 Drought tolerant varieties

We then turn to the case of drought tolerant varieties. Such varieties make land more profitable.[8] We will thus assume that this corresponds to technical change biased towards land, and suppose that $\hat{a}_l > 0$, and $\hat{\alpha} = \hat{a}_p = 0$. Obviously, this is a rather strong simplification (as although focusing on pesticide efficiency, insect resistant varieties probably increase land efficiency and total factors productivity as well), but it provides an interesting illustration of "land-biased technical change" (Hertel, 2012). The following proposition then holds:

Proposition 2: If innovation is land biased, the use of pesticides increases with innovation if and only if the demand for agricultural output is more elastic than production factors are substitutable ($\varepsilon_d > \sigma$). Land use decreases with innovation if and only if either both elasticities of demand for output and factors substitutions are small, or, if demand (substitution, respectively) elasticity only is small, the share of pesticides (land, respectively) in total cost is small enough.

The proof of this proposition is in appendix. The expression for the variations in land and pesticides use are given by:

$$\hat{x}_l = \frac{\varepsilon_l \left(\theta_l \varepsilon_d + \theta_p \sigma - 1\right)}{\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d} \hat{a}_l \tag{2.10}$$

[8] Land subject to severe drought may be cultivated, and even plots that are not particularly dry may require less irrigation.

$$\hat{x_p} = \frac{\theta_l \left(\varepsilon_d - \sigma\right) \left(1 + \varepsilon_l\right)}{\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d} \hat{a_l} \tag{2.11}$$

When innovation is biased towards one of the inputs, it is rather straightforward that the role played by substitutability of factors in determining the use of inputs will be much more critical. We first discuss how the magnitude of $\hat{x_l}/\hat{\alpha}$ and $\hat{x_p}/\hat{\alpha}$ vary with the model parameters. The elasticity of demand plays a similar role here to the one it had in Hicks-neutral innovation: the more elastic demand is, the more farmers will be able to increase their production on the extensive margin without bearing the consequences on prices of the increase in production, and then both land and pesticide use increase with consumers' demand elasticity. In addition, *ceteris paribus*, it is quite intuitive that the more substitutable factors are (*i.e.* the higher σ), the more likely an increase in marginal productivity of land will encourage the farmers to swap from pesticides to land as land becomes a more efficient input factor relatively to pesticides. This is why x_l and x_p (and not only their absolute value, as in the previous section) are respectively increasing and decreasing with σ.

We now discuss the respective signs of $\hat{x_p}/\hat{a_l}$ and $\hat{x_l}/\hat{a_l}$. Although, as in the case of Hicks-neutral innovation, the elasticity of demand is still a key parameter to determine whether the use of pesticides will increase following the introduction of a land biased innovation, it should now be compared to the elasticity of substitutions of inputs. Indeed, factors substitution and price effects have opposite consequences on pesticide use as explained in the previous paragraph, so the overall effect of innovation depends on the relative magnitudes of demand and substitution elasticities. The case of land use deserves a deeper analysis. If both demand and factors substitutions elasticities are large (both larger than 1), a land-biased innovation will lead to an increase in land use. Indeed, if demand elasticity is large, the increase in production will occur largely on the extensive margin, without much price variation. If, in addition, factors are easily substitutable, the farmers will substitute land for pesticides, increasing even further land extension. Reciprocally, if both are small (both smaller than 1), a land-biased innovation will lead to a decrease in land use. Now if one of these elasticities is large and the other one is small, the critical parameter is the share of, say, land in total costs. To exemplify this, consider the case where the elasticity of substitution is large and demand elasticity is small. If land costs is a large share of total costs ($\theta_l \approx 1$), then the effect of substitution will be negligible: even if inputs are easily substitutable, the farmers will not aim to substitute much of pesticides by land, as pesticides are only a small share of their total costs. If, on the contrary, pesticides represent a large share of total costs ($\theta_l \approx 0$), then it will be very profitable for farmers to substitute land to pesticides.

The effect of an increase in land supply elasticity on the magnitude of pesticides use change (be it positive or negative) depends on the the effect of innovation on land use. If the introduction of the innovation extends cultivated surface (*i.e.* $\theta_l \varepsilon_d + \theta_p \sigma > 1$), then an increase in land elasticity of supply increases the magnitude of the effect of innovation on pesticides use. If, on the contrary, the introduction of the innovation causes a contraction of cultivated surface, then an increase in land elasticity of supply decreases the magnitude of the effect of innovation on pesticides use. This can be interpreted quite easily, as an elastic supply of land extends somehow an improvement in efficiency of land. Indeed, if land supply is not very elastic, the improvement of land efficiency is quickly offset by the increase in land price consecutive to the stronger demand. On the contrary, if land supply is elastic, the increase in land prices that will follow the improvement will be moderated, maintaining the comparative advantage of land with respect to the other input.

Land biased innovation may “spare land for nature” (Ewers et al., 2009) if the demand is sufficiently inelastic and production factors are not very substitutable. Moreover, if these conditions are met and elasticity of demand is larger that factors elasticity of substitution, then land biased innovation will lead to *land sparing* in the acception of Green et al. (2005), *i.e.* intensification of cultivated land associated with a reduction of agricultural surfaces.

2.3 Insect resistant varieties

We finally consider the case of insect resistant (IR) varieties, such as *Bt* crops. *Bt* crops are protected against some specific pests, but not agains all of them. Hence, they still need the use of pesticides to fight agains the plagues that are not *Bt* sensitive. However, they allow farmers to use a tighter spectrum of pesticides, that is more efficient than those spread on non *Bt* crops (Qaim, 2009). Assume thus that this kind of innovation is biased in favor of pesticides.

Proposition 3: If innovation is pesticide biased, the use of land increases with innovation if and only if the demand for agricultural output is more elastic than production factors are substitutable ($\varepsilon_d > \sigma$). If demand is inelastic and production factors are hardly substitutable, then the use of pesticides decrease with innovation. Moreover, if pesticides hold a large share of total costs for farmers, then inelastic demand and hardly substitutable production factors are necessary and sufficient condition for pesticides use decrease.

The variation in land and pesticides use is then:

$$\hat{x_l} = \frac{\theta_p \varepsilon_l \left(\varepsilon_d - \sigma\right)}{\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d} \hat{a_p} \tag{2.12}$$

$$\hat{x_p} = \frac{(\sigma - 1)(\varepsilon_l + \varepsilon_d) + \theta_p(\varepsilon_d - \sigma)(1 + \varepsilon_l)}{\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d} \hat{a_p} \tag{2.13}$$

Land under pesticides-biased innovation is somehow symmetrical to pesticides under land-biased innovation, and the impacts of the parameters on innovation effect on land use is analogous. The intuitions explained in the previous section for pesticides use hold here for land use. Land use decreases with innovation if and only if elasticity of demand is larger than production factors substitutability ($\varepsilon_d > \sigma$). The magnitude of the effect of innovation on land use is all the larger that pesticides represent a large share of total costs, because it is then all the more profitable for the farmers to try reduce their use of pesticides by substituting land to it.

As in the case of Hicks-neutral innovation, inelastic demand is likely to lead to a decrease in inputs use. However, as a pesticide biased innovation will improve the efficiency of pesticides, and there is thus a possibility that farmers will strive to substitute pesticides to land, especially if land represents a large share of total production costs. Hence, factors should be hardly substitutable to avoid increase in pesticides use. Hence, if $\sigma < 0$ and $\varepsilon_d < 1$, then no increase in pesticides use will follow the introduction of the innovation. If pesticides represent the largest share of total costs ($\theta_p \approx 1$), substitution of land by pesticides will not be particularly profitable for farmers. Most of the increase in pesticides use will then be triggered by the demand effect, which explains why a low elasticity of demand will be sufficient, in that case, to ensure no increase in pesticides use. Reciprocally, if land represents a large share of total costs ($\theta_p \approx 0$), then farmers will try to reduce their consumption of land and substitute land by pesticides, whatever the effect of innovation on inputs in general. In that case, whatever the elasticity of demand, substitutability of factors will be the crucial factor, and low substitutability will be sufficient to avoid a low increase in pesticides use.

Pesticides biased innovation is land sparing if and only if demand elasticity is smaller than production factors substitution elasticity. For such type of innovation to be land sparing as defined by the ecological literature, it should additionally be the case that both factors substitution and demand elasticities' absolute values are small as well.

2.4 Comparison with empirical results

It would be very interesting to confront out theoretical analysis to empirical evaluations of the impact on land and pesticides use of the introduction of different types of GM crops. However, the empirical evidence is still rather scarce. In particular, to our knowledge, no study estimates the consequences of GM adoption on both input use simultaneously.[9]. The mixed results on the impact of innovation on land use we pointed in introduction is a first support to our approach.[10] However, the studies we reviewed do not mention the type of innovation that have been provided to the farmers, and it is thus difficult to provide a consistent discussion regarding land use.

A few empirical analyses are available, however, regarding the use of pesticides. Focusing on the US, Benbrook (2012) found that the diffusion of herbicide resistant varieties of cotton and soybean led to an increase in the use of herbicides per acre (+43% for cotton over the 1996-2010 period, and +21% for soybean between 1996 and 2006). The adoption of HR corn decreased the quantity of herbicide spread per acre on cultivated surfaces (-15% over the 1996-2010 period). Despite the difficulties in estimating elasticities of demand for crops, calibrating our models with existing estimates lead to results that are partially contradicted by these empirical reults. The Food and Agricultural Policy Research Institute (2016) database does not provide estimates for elasticity of demand for corn in the US, but in other regions, they estimate it to be around -0.2. However, the Institute also estimates demand elasticity for soybeans to be only slightly larger, around -0.3, and Price et al. (2003) reviewed several works that estimated the elasticity of demand for cotton in the US around -0.3 as well. Based on such values, our model predicts that the use of pesticides would decrease following the improvement of HR varieties of each crop. Several

[9]Using results from different studies - one on the impact on land use and another on the impact on chemical use - requires caution to account for heterogeneity in the methods of evaluation.

[10]If the impact of innovation depends, among other factors, on the type of innovation, it is not surprising that studies considering different types of innovations find different results.

reasons may explain this gap. First, the estimates of elasticities are subject to important uncertainty. Second, and more importantly, Benbrook compared the use of pesticide before and after the introduction of GM crops, which is a breakthrough. Yet, our model assumes more incremental improvements (eg the introduction of more efficient genes in already biotech plants). Benbrook also estimated that the adoption of *Bt* corn and cotton significantly reduced the use of pesticides. Such estimates is more consistant with the predictions of our model, accounting for the very low values for elasticity of demand for these commodities. As far as we know, such type of estimates do not exist for drought tolerant crops.

Despite the existence of a few studies that shed some empirical light on our theoretical results, being more conclusive would require further work. First, it would be interesting to extend the works on the impact of innovation on land use, focusing on genetically modified crops, and distinguishing by the type of modification. Second, studying the effect of adoption of drought tolerant varieties would bring significant additional information. Third, an empirical evaluation of our model should examine the impact of incremental improvement of GM varieties rather than the impact of introduction of GM varieties *per se*. Uncertainties on the estimation of elasticities of demand remains, however, a significant difficulty, that prevents clear-cut conclusions about the empirical validation of our results.

3 Discussion

3.1 Market effects of agricultural innovation on land sparing

The extension of Hertel (2012) we present here allows to study the market effects of the introduction of different types of innovation, beyond land use. It thus enhances the existing framework of analysis of the land sharing/land sparing debate. Its objective is to question the visions that, in the absence of public intervention, innovation would either be able to spare land (the Borlaug's hypothesis) or would cause both the extension and intensification of cultures (the Jevons's paradox). We have shown that the actual outcome is in fact more mixed and relies heavily on the structures of demand for and production of the agricultural commodity, which may well explain the absence of clear-cut empirical results highlighted in the introduction.

The first contribution of this study is that it complements knowledge on the consequences of the adoption of agricultural innovation on its environment. We highlighted that the introduction of an improved variety will modify the total cultivated surface and the intensity of other inputs use. Our results complement those obtained by Barrows et al. (2013) in several respects. First, they assume exogenous prices (which, in our setting, corresponds to perfectly elastic demand, $\varepsilon_d \to +\infty$). Under such assumption, they find that the adoption of innovation always increases production at the extensive margin, *i.e.* causes an increase in land use, which is consistent with our findings in the particular case of elastic demand. Second, they examine the effect of a generic innovation in genetically engineered crops that reduces pest pressure on cultivated fields. We adopt a more specific point of view, which distinguishes between the three main families of existing GM varieties. Improving one type of varieties may favor the efficiency of one production factor more than others'. This allows us to show that the outcome of innovation actually depends on the input which productivity is improved by the innovation. Our study builds on the paper by Hertel (2012), which focused on innovation's impact on land use (and its consecutive greenhouse gas emissions), and on Hicks-neutral and land-biased innovations. Our study complements his, as we also examine the impact of innovation on pesticides use, and extend the analysis to pesticides biased innovation as well.

The second contribution of this study is to clarify the articulation between agricultural innovation and biodiversity conservation issues. We find that except when Hicks-neutral, an innovation in agricultural varieties does not necessarily change land and pesticides use in the same direction: farmers will try to use more of the input that is favored by innovation (especially if it represents a small share of total production costs) as it gets more efficient, and will do so all the more easily that factors are substitutable. A large share of the land sharing/land sparing literature considers the possibility of sparing for a given technology, through intensification (in particular by using more chemicals) of existing varieties . However, the literature on land sparing has acknowledged the potential role of innovation (Waggoner, 1995; Ewers et al., 2009). We complement this literature by taking demand effects into account. We hence show that the full potential of intensification following may not be attained by market mechanisms, especially when innovation cause simultaneously reduction in land and pesticides use.

3.2 Crops at the crossroads of agricultural research and conservation policies

The theoretical analysis we have conducted sheds some light on the interface between research and conservation policies. Public policies have been at the core of research on agricultural varieties throughout the 20$^{\text{th}}$ century. Until the late 1980s, most plant breeding in the US was undertaken by public research (Fernandez-Cornejo, 2004, Fig. 14). Conservation of biodiversity has also been an important intervention field for agricultural policies. It is, for instance, one of the goals targeted by the second pillar of the European common agricultural policy. It is thus straightforward to endeavor to find synergies between these policies. Our study shows that R&D on varieties may prove a useful tool that should be integrated to policies targeting biodiversity protection. However, we also mitigate this "double dividend" of simultaneous increased productivity of agriculture and biodiversity conservation brought by agricultural innovation. We first highlight, after Hertel (2012), the role of demand characteristics and the weakness of reasoning on the consequences of innovation holding output quantity constant. This finding does not allow to conclude that innovation will save inputs in any case. We also show that even after innovation is discovered, market equilibrium may not lead to either wide, low intensity agricultural lands or concentrated, intensive cultures. Hence, research policy orientation may be a necessary but not sufficient answer to conservation issues.

Depending on how biodiversity density reacts to cultures intensity, policymakers may target an objective of either extensive or intensive cultures (Green et al., 2005). If species suffer a lot from low levels of intensification, research policy should support innovation that will favor an increase in the use of pesticides rather than land. If, on the contrary, most of species loss occurs after a high level of intensification, research policy should encourage innovation that will favor an increase in the use of land rather than pesticides. This is rather easy for crops for which these factors are hardly substitutable: pesticides-biased innovation should be supported in the first case, while land-biased innovation should be supported in the second case. In the case of crops for which factors are more substitutable, market equilibrium may not be optimal from a social planner point of view, and it may be desirable that an environmental regulation on the market complements the research policy. It should be noted that regulation can decrease substitutability of factors, by imposing restrictions on pesticides use for instance.

3.3 Perspectives

It would be interesting to complement our study with some further developments. First, some of the assumptions we have made could be relaxed to enrich the conclusions of the model. We have considered that once the innovation is developed, it is immediately adopted by all farmers, and this is done at zero cost. Such design would have matched reality in the first part of the 20th century, when most research was conducted by governmental agencies and distributed almost for free to farmers. After the development of hybrid varieties in the 1930s, and of intellectual property rights over plants from the 1970s on, the private sector has substituted, to some extent, to the private sector. Farmers are thus provided with a choice of various improved varieties, marketed for different prices, and shall chose amont them which variety suits their needs best. For an innovation to produce the environmental effects described in our study, it is necessary that they are adopted by farmers, and accounting for the decision of adoption would make the model more relevant.

Second, we have supposed, in our analysis, that the objective of the social planner is defined (for instance, while increasing total output, reducing land use and increasing concentration to spare land for biodiversity), and we suggest ways to reach it. It would significantly enhance the applicability of our results to conduct a broader welfare analysis, in order to make the decision to provide improved varieties endogenous. However, doing so would require to solve several technical issues. First, it would be necessary to understand more precisely how biodiversity reacts to extension and intensification of cultures. Such topic is still under investigation in the academic literature in ecology (Hulme et al., 2013; Phalan et al., 2014). Second, it would also be necessary to specify welfare associated with biodiversity conservation.

Finally, it is quite likely that innovation and productivity gains on the agricultural commodity market will trigger changes on other markets: higher wages on the labour market and returns on the capital market, changes in consumption behaviors, etc. These general equilibrium effects are not captured by partial equilibrium models, as noted by Villoria et al. (2014). They probably make Jevons's paradox slightly more likely to occur and it would be interesting to study them in a general equilibrium analysis.

Appendix

Assume the following constant elasticity production function, of elasticity $\sigma = 1/(1+\rho)$, where $\rho > -1$:

$$y = \alpha \left(\lambda x_l^{-\rho} + \phi x_p^{-\rho} \right)^{-1/\rho} \tag{2.14}$$

Denote p_l and p_p the respective prices of land and pesticides. Assume that farmers are sufficiently small to take these prices as exogenous. The cost minimization programme of the farmers is then:

$$\begin{aligned} &\min_{x_l, x_p} C(y, x_l, x_p) = p_l x_l + p_p x_p \\ &\text{s. t. } y = \alpha \left(\lambda x_l^{-\rho} + \phi x_p^{-\rho} \right)^{-1/\rho} \end{aligned} \tag{2.15}$$

The Lagrangian of this optimization problem is, with μ the Lagrange multiplier:

$$\mathcal{L}(x_l, x_p, \mu) = p_l x_l + p_p x_p - \mu \left[y - \alpha \left(\lambda x_l^{-\rho} + \phi x_p^{-\rho} \right)^{-1/\rho} \right]$$

Associated first order conditions are:

$$\frac{\partial \mathcal{L}}{\partial x_l} = 0 \quad \Leftrightarrow \quad p_l = -\mu \alpha \lambda x_l^{-\rho-1} \left(\lambda x_l^{-\rho} + \phi x_p^{-\rho} \right)^{-(1+\rho)/\rho} \tag{2.16}$$

$$\frac{\partial \mathcal{L}}{\partial x_l} = 0 \quad \Leftrightarrow \quad p_p = -\mu \alpha \phi x_p^{-\rho-1} \left(\lambda x_l^{-\rho} + \phi x_p^{-\rho} \right)^{-(1+\rho)/\rho} \tag{2.17}$$

$$\frac{\partial \mathcal{L}}{\partial \mu} = 0 \quad \Leftrightarrow \quad y = \alpha \left(\lambda x_l^{-\rho} + \phi x_p^{-\rho} \right)^{-1/\rho} \tag{2.18}$$

Dividing (2.16) by (2.17) yields the equality of the marginal rate of substitution to the quotient of prices:

$$\frac{p_l}{p_p} = \frac{\lambda x_l^{-\rho-1}}{\phi x_p^{-\rho-1}} \tag{2.19}$$

Or, equivalently:

$$x_p = x_l \left(\frac{\phi p_l}{\lambda p_p} \right)^{1/(1+\rho)} \tag{2.20}$$

Rearranging terms in (2.14) and substituting (2.20) yields:

$$\left(\frac{y}{\alpha} \right)^{-\rho} = \lambda x_l^{-\rho} + \phi x_l^{-\rho} \left(\frac{\phi p_l}{\lambda p_p} \right)^{-\rho/(1+\rho)} \tag{2.21}$$

Rearranging terms yields:

$$\left(\frac{y}{\alpha}\right)^{-\rho} = x_l^{-\rho}\left(\frac{p_l}{\lambda}\right)^{-\rho/(1+\rho)}\left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\right]$$

Then we get the farmers' demands for land and pesticides[11], respectively:

$$x_l = \frac{y}{\alpha}\left(\frac{\lambda}{p_l}\right)^{1/(1+\rho)}\left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\right]^{1/\rho} \quad (2.22)$$

$$x_p = \frac{y}{\alpha}\left(\frac{\phi}{p_p}\right)^{1/(1+\rho)}\left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\right]^{1/\rho} \quad (2.23)$$

The unit cost of production c is then:

$$c = \frac{\left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\right]^{(1+\rho)/\rho}}{\alpha} \quad (2.24)$$

It should be noted that c depends on the output level (c is thus not equal to marginal cost), as the prices of inputs p_l and p_p *a priori* depend on the total quantities of used inputs. The demand for inputs can then be written, with $\sigma = 1/(1+\rho)$ the constant elasticity of substitution:

$$x_l = \frac{y}{\alpha}\left(\frac{\lambda\alpha c}{p_l}\right)^{\sigma} \quad (2.25)$$

$$x_p = \frac{y}{\alpha}\left(\frac{\phi\alpha c}{p_p}\right)^{\sigma} \quad (2.26)$$

We first linearize (2.25) and (2.26). Taking the logarithm of the these equations yields:

$$\ln(x_l) = \ln(y) - \ln(\alpha) + \sigma\left[\ln(\lambda) + \ln(\alpha) + \ln(c) - \ln(p_l)\right] \quad (2.27)$$

$$\ln(x_p) = \ln(y) - \ln(\alpha) + \sigma\left[\ln(\phi) + \ln(\alpha) + \ln(c) - \ln(p_p)\right] \quad (2.28)$$

Denoting $\hat{u}$ the relative variation of variable u ($\hat{u} = du/u$), the total differentiation of (2.27) and (2.28) yields:

$$\hat{x}_l = \hat{y} - \hat{\alpha} + \sigma\left[\hat{\lambda} + \hat{\alpha} + \hat{c} - \hat{p}_l\right] \quad (2.29)$$

[11]To get the demand for pesticides, we can either substitute (2.22) in (2.20), or call on symmetry arguments.

$$\hat{x_p} = \hat{y} - \hat{\alpha} + \sigma\left[\hat{\phi} + \hat{\alpha} + \hat{c} - \hat{p_p}\right] \tag{2.30}$$

We now intend to linearize (2.24). Multiplying by α and totally differentiating this equation yields:

$$\begin{aligned} cd\alpha + \alpha dc &= \frac{1+\rho}{\rho}\left[\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)}\right]^{1/\rho} \\ &\quad d\left[\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)}\right] \end{aligned} \tag{2.31}$$

Yet:

$$\begin{aligned} d\left[\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)}\right] &= d\left[\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)}\right] + d\left[\phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)}\right] \\ &= \lambda^{1/(1+\rho)} d\left[p_l^{\rho/(1+\rho)}\right] + p_l^{\rho/(1+\rho)} d\left[\lambda^{1/(1+\rho)}\right] \\ &\quad + \phi^{1/(1+\rho)} d\left[p_p^{\rho/(1+\rho)}\right] + p_p^{\rho/(1+\rho)} d\left[\phi^{1/(1+\rho)}\right] \\ &= \frac{\rho}{1+\rho}\lambda^{1/(1+\rho)} p_l^{-1/(1+\rho)} dp_l + \frac{1}{1+\rho} p_l^{\rho/(1+\rho)} \lambda^{-\rho/(1+\rho)} d\lambda \\ &\quad + \frac{\rho}{1+\rho}\phi^{1/(1+\rho)} p_p^{-1/(1+\rho)} dp_p + \frac{1}{1+\rho} p_p^{\rho/(1+\rho)} \phi^{-\rho/(1+\rho)} d\phi \\ &= \frac{\rho}{1+\rho}\left[\lambda^{1/(1+\rho)} p_l^{-1/(1+\rho)} dp_l + \frac{1}{\rho} p_l^{\rho/(1+\rho)} \lambda^{-\rho/(1+\rho)} d\lambda \right. \\ &\quad \left. + \phi^{1/(1+\rho)} p_p^{-1/(1+\rho)} dp_p + \frac{1}{\rho} p_p^{\rho/(1+\rho)} \phi^{-\rho/(1+\rho)} d\phi\right] \\ &= \frac{\rho}{1+\rho}\left[\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)} \frac{dp_l}{p_l} + \frac{1}{\rho} p_l^{\rho/(1+\rho)} \lambda^{1/(1+\rho)} \frac{d\lambda}{\rho\lambda} \right. \\ &\quad \left. + \phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)} \frac{dp_p}{p_p} + \frac{1}{\rho} p_p^{\rho/(1+\rho)} \phi^{1/(1+\rho)} \frac{d\phi}{\rho\phi}\right] \\ &= \frac{\rho}{1+\rho}\left[\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)} \left(\frac{dp_l}{p_l} + \frac{d\lambda}{\rho\lambda}\right) \right. \\ &\quad \left. + \phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)} \left(\frac{dp_p}{p_p} + \frac{d\phi}{\rho\phi}\right)\right] \end{aligned}$$

And :

$$cd\alpha + \alpha dc = c\alpha\left(\frac{d\alpha}{\alpha} + \frac{dc}{c}\right)$$

(2.31) thus becomes:

$$\begin{aligned}
c\alpha\left(\frac{d\alpha}{\alpha}+\frac{dc}{c}\right) &= \left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\right]^{1/\rho} \\
&\quad \left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}\left(\frac{dp_l}{p_l}+\frac{d\lambda}{\rho\lambda}\right)+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\left(\frac{dp_p}{p_p}+\frac{d\phi}{\rho\phi}\right)\right] \\
&= \frac{\left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\right]^{(1+\rho)/\rho}}{\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}} \\
&\quad \left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}\left(\frac{dp_l}{p_l}+\frac{d\lambda}{\rho\lambda}\right)+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\left(\frac{dp_p}{p_p}+\frac{d\phi}{\rho\phi}\right)\right]
\end{aligned}$$

Yet, from (2.24), $\left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\right]^{(1+\rho)/\rho}=c\alpha$, so:

$$\begin{aligned}
c\alpha\left(\frac{d\alpha}{\alpha}+\frac{dc}{c}\right) &= \frac{c\alpha}{\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}} \\
&\quad \left[\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}\left(\frac{dp_l}{p_l}+\frac{d\lambda}{\rho\lambda}\right)+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}\left(\frac{dp_p}{p_p}+\frac{d\phi}{\rho\phi}\right)\right]
\end{aligned}$$

Hence:

$$\begin{aligned}
\frac{d\alpha}{\alpha}+\frac{dc}{c} &= \frac{\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}}{\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}}\left(\frac{dp_l}{p_l}+\frac{d\lambda}{\rho\lambda}\right) \quad (2.32)\\
&\quad +\frac{\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}}{\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}}\left(\frac{dp_p}{p_p}+\frac{d\phi}{\rho\phi}\right) \quad (2.33)
\end{aligned}$$

Moreover:

$$\begin{aligned}
\frac{\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}+\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}}{\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}} &= 1+\frac{\phi^{1/(1+\rho)}p_p^{\rho/(1+\rho)}}{\lambda^{1/(1+\rho)}p_l^{\rho/(1+\rho)}} \\
&= 1+\frac{p_p}{p_l}\frac{\phi^{1/(1+\rho)}p_p^{-1/(1+\rho)}}{\lambda^{1/(1+\rho)}p_l^{-1/(1+\rho)}} \\
&= 1+\frac{p_p}{p_l}\left(\frac{\phi p_l}{\lambda p_p}\right)^{1/(1+\rho)} \quad (2.34)
\end{aligned}$$

From (2.19):

$$\frac{\phi p_l}{\lambda p_p}=\left(\frac{x_p}{x_l}\right)^{\rho+1} \quad (2.35)$$

(2.34) then becomes:

$$\frac{\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)}}{\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)}} = 1 + \frac{p_p x_p}{p_l x_l} = \frac{p_l x_l + p_p x_p}{p_l x_l} \tag{2.36}$$

Similarly:

$$\frac{\lambda^{1/(1+\rho)} p_l^{\rho/(1+\rho)} + \phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)}}{\phi^{1/(1+\rho)} p_p^{\rho/(1+\rho)}} = \frac{p_l x_l + p_p x_p}{p_p x_p} \tag{2.37}$$

Hence, (2.33) becomes:

$$\frac{d\alpha}{\alpha} + \frac{dc}{c} = \frac{p_l x_l}{p_l x_l + p_p x_p}\left(\frac{dp_l}{p_l} + \frac{d\lambda}{\rho\lambda}\right) + \frac{p_p x_p}{p_l x_l + p_p x_p}\left(\frac{dp_p}{p_p} + \frac{d\phi}{\rho\phi}\right) \tag{2.38}$$

Define θ_l and θ_p as the respective shares of land and pesticides costs in production:

$$\theta_l = \frac{p_l x_l}{p_l x_l + p_p x_p} \qquad \theta_p = \frac{p_p x_p}{p_l x_l + p_p x_p} \tag{2.39}$$

Then (2.38) can be written:

$$\hat{\alpha} + \hat{c} = \theta_l \left(\hat{p_l} + \frac{\hat{\lambda}}{\rho}\right) + \theta_p \left(\hat{p_p} + \frac{\hat{\phi}}{\rho}\right) \tag{2.40}$$

Denoting p_y the unit price of output, he zero profit condition for the farmers is $p_y y - cy = 0$, which is equivalent to $c = p_y$. Then, defining $\hat{a_l} = -\hat{\lambda}/\rho$ and

$\hat{a_p} = -\hat{\phi}/\rho$[12] (2.29), (2.30) and (2.40) yield the set of equations:

$$\hat{x_l} + \hat{a_l} = \hat{y} - \hat{\alpha} + \sigma\left[\hat{\alpha} + \hat{p_y} + \hat{a_l} - \hat{p_l}\right] \tag{2.42}$$

$$\hat{x_p} + \hat{a_p} = \hat{y} - \hat{\alpha} + \sigma\left[\hat{\alpha} + \hat{p_y} + \hat{a_p} - \hat{p_p}\right] \tag{2.43}$$

$$\hat{\alpha} + \hat{p_y} = \theta_l\left(\hat{p_l} - \hat{a_l}\right) + \theta_p\left(\hat{p_p} - \hat{a_p}\right) \tag{2.44}$$

Linearizing these assumptions that $y = p_y^{-\varepsilon_d}$ and $x_l = p_l^{\varepsilon_l}$ yields:

$$\hat{y} = -\varepsilon_d \hat{p_y} \tag{2.45}$$

$$\hat{p_p} = 0 \tag{2.46}$$

$$\hat{x_l} = \varepsilon_l \hat{p_l} \tag{2.47}$$

Then subtracting (2.42) from (2.43), and substituting the expressions of $\hat{p_y}$, $\hat{p_p}$ and $\hat{p_l}$ from (2.45), (2.46) and (2.47) respectively yields the following set of equations:

$$\hat{x_p} = (\sigma - 1)\left(\hat{a_p} - \hat{a_l}\right) + \left(1 + \frac{\sigma}{\varepsilon_l}\right)\hat{x_l} \tag{2.48}$$

$$\hat{x_l} = \hat{y} + (\sigma - 1)\hat{\alpha} + (\sigma - 1)\,\hat{a_l} - \sigma\left(\frac{\hat{y}}{\varepsilon_d} + \frac{\hat{x_l}}{\varepsilon_l}\right) \tag{2.49}$$

$$\hat{\alpha} - \frac{\hat{y}}{\varepsilon_d} = \theta_l\left(\frac{\hat{x_l}}{\varepsilon_l} - \hat{a_l}\right) - \theta_p \hat{a_p} \tag{2.50}$$

[12] Defining $\hat{a_i}$ for $i \in \{l, p\}$ is handy because it avoids a discussion according to the sign of ρ: a positive $\hat{a_i}$ is equivalent to an increase in the marginal productivity of factor i, whatever the value of $\rho > -1$ (while, on the contrary, the effect on y of an increase in λ or ϕ depends on the sign of ρ). Indeed, for $i = l$ (the case $i = p$ is perfectly symmetrical) :

$$\frac{\partial y}{\partial \lambda} = -\frac{\alpha}{\rho} x_l^{-\rho}\left(\lambda x_l^{-\rho} + \phi x_p^{-\rho}\right)^{-(1+\rho/\rho)} \tag{2.41}$$

Hence, if $\rho \geq 0$, the RHS of (2.41) is negative and an increase in a_l is equivalent to a decrease in λ. Similarly, if $\rho \leq 0$, an increase in a_l, the RHS of (2.41) is positive and an increase in a_l is equivalent to an increase in λ. Hence, an increase in a_l is associated with an increase in y.

Herbicide tolerant varieties

Proof of proposition 1: Assume $\hat{\alpha} > 0$, $\hat{a_p} = \hat{a_l} = 0$. Plugging this into (2.48), (2.49) and (2.83) yields:

$$\hat{x_p} = \left(1 + \frac{\sigma}{\varepsilon_l}\right)\hat{x_l} \tag{2.51}$$

$$\hat{x_l} = \hat{y} + (\sigma - 1)\hat{\alpha} - \sigma\left[\frac{\hat{y}}{\varepsilon_d} + \frac{\hat{x_l}}{\varepsilon_l}\right] \tag{2.52}$$

$$\hat{\alpha} - \frac{\hat{y}}{\varepsilon_d} = \theta_l \frac{\hat{x_l}}{\varepsilon_l} \tag{2.53}$$

Substituting the expression of $\hat{y}$ from (2.53) in (2.52) yields:

$$\hat{x_l}\left(1 + \frac{\sigma}{\varepsilon_l}\right) = \left[\varepsilon_d\hat{\alpha} - \frac{\varepsilon_d\theta_l}{\varepsilon_l}\hat{x_l}\right]\left(1 - \frac{\sigma}{\varepsilon_d}\right) + (\sigma - 1)\hat{\alpha} \tag{2.54}$$

which becomes, rearranging terms:

$$\hat{x_l}\left[\frac{\varepsilon_l + \sigma + \varepsilon_d\theta_l - \theta_l\sigma}{\varepsilon_l}\right] = (\varepsilon_d - 1)\,\hat{\alpha} \tag{2.55}$$

Finally, recalling $1 - \theta_l = \theta_p$, we get the expression for x_l:

$$\hat{x_l} = \frac{\varepsilon_l\,(\varepsilon_d - 1)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{\alpha} \tag{2.56}$$

The expression for $\hat{x_p}$ follows immediately from (2.51):

$$\hat{x_p} = \frac{(\varepsilon_l + \sigma)\,(\varepsilon_d - 1)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{\alpha} \tag{2.57}$$

Q.E.D.

It is useful to check that total output increases with innovation. The expression for $\hat{y}$ is derived substituting $\hat{x_l}$ (2.56) in (2.53):

$$\hat{y} = \frac{\varepsilon_l + \theta_p\sigma + \theta_l}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{\alpha} \tag{2.58}$$

which is positive indeed if and only if $\hat{\alpha}$ is. Finally the change in land and output prices are:

$$\hat{p_l} = \frac{(\varepsilon_d - 1)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{\alpha} \tag{2.59}$$

$$\hat{p_y} = -\frac{\varepsilon_l + \theta_p\sigma + \theta_l}{\varepsilon_d\left(\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d\right)}\hat{\alpha} \tag{2.60}$$

Moreover, taking absolute value and differentiating (2.56) and (2.57) yields:

$$\frac{\partial|\hat{x_l}|}{\partial\sigma} = \frac{-\theta_p\varepsilon_l}{\left(\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d\right)^2}|\varepsilon_d - 1||\hat{\alpha}| < 0 \tag{2.61}$$

An increase in production factors substitutability σ decreases the magnitude of the effect of Hicks neutral innovation on the variation in land use.

$$\frac{\partial|\hat{x_p}|}{\partial\sigma} = \frac{\theta_l(\varepsilon_l + \varepsilon_d)}{\left(\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d\right)^2}|\varepsilon_d - 1||\hat{\alpha}| \tag{2.62}$$

An increase in σ increases the magnitude of the effect of Hicks neutral innovation on the variation in pesticides use.

$$\frac{\partial|\hat{x_l}|}{\partial\varepsilon_l} = \frac{\theta_p\sigma + \theta_l\varepsilon_d}{\left(\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d\right)^2}\,|\varepsilon_d - 1|\,|\hat{\alpha}| \tag{2.63}$$

An increase in land supply elasticity ε_l increases the magnitude of the effect of Hicks neutral innovation on the variation in land use.

$$\frac{\partial|\hat{x_p}|}{\partial\varepsilon_l} = \frac{\theta_l(\varepsilon_d - \sigma)}{\left(\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d\right)^2}\,|\varepsilon_d - 1|\,|\hat{\alpha}| \tag{2.64}$$

An increase in ε_l increases the magnitude of the effect of Hicks neutral innovation on the variation in land use if and only if $\varepsilon_d \geq \sigma$.

Drought tolerant varieties

Proof of proposition 2: Suppose that $\hat{a}_l > 0$, and $\hat{\alpha} = \hat{a}_p = 0$. Plugging this into (2.48), (2.49) and (2.50)

$$\hat{x_p} = (1-\sigma)\,\hat{a}_l + \left(1 + \frac{\sigma}{\varepsilon_l}\right)\hat{x}_l \tag{2.65}$$

$$\hat{x}_l = \hat{y} + (\sigma - 1)\,\hat{a}_l - \sigma\left(\frac{\hat{y}}{\varepsilon_d} + \frac{\hat{x}_l}{\varepsilon_l}\right) \tag{2.66}$$

$$-\frac{\hat{y}}{\varepsilon_d} = \theta_l\left(\frac{\hat{x}_l}{\varepsilon_l} - \hat{a}_l\right) \tag{2.67}$$

From (2.67), we get the following expression for $\hat{y}$:

$$\hat{y} = \theta_l\varepsilon_d\hat{a}_l - \frac{\theta_l\varepsilon_d}{\varepsilon_l}\hat{x}_l \tag{2.68}$$

and simplifying (2.66) yields:

$$\hat{x}_l\left(1 + \frac{\sigma}{\varepsilon_l}\right) = \hat{y}\left(1 - \frac{\sigma}{\varepsilon_d}\right) + (\sigma - 1)\hat{a}_l \tag{2.69}$$

Substituting the expression of $\hat{y}$ from (2.67) in (2.66) yields:

$$\hat{x}_l\left(1 + \frac{\sigma}{\varepsilon_l}\right) = \left(\theta_l\varepsilon_d\hat{a}_l - \frac{\theta_l\varepsilon_d}{\varepsilon_l}\hat{x}_l\right)\left(1 - \frac{\sigma}{\varepsilon_d}\right) + (\sigma - 1)\hat{a}_l \tag{2.70}$$

Using the fact that $1 - \theta_l = \theta_p$ yields the relative variation in land use:

$$\hat{x}_l = \frac{\varepsilon_l\left(\theta_l\varepsilon_d + \theta_p\sigma - 1\right)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{a}_l \tag{2.71}$$

$$\hat{x_p} = \frac{\theta_l\left(\varepsilon_d - \sigma\right)\left(1 + \varepsilon_l\right)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{a}_l \tag{2.72}$$

Then $\hat{x_p}/\hat{a}_l > 0$ if and only if $\varepsilon_d > 0$, and $\hat{x}_l/\hat{a}_l > 0$ if and only if $\theta_l\varepsilon_d + \theta_p\sigma - 1 > 0$. It is useful to note that, using $\theta_p + \theta_l = 1$, $\theta_l\varepsilon_d + \theta_p\sigma$ always lies between ε_d and σ. Hence, if $\min\{\varepsilon_d, \sigma\} > 1$, then $\hat{x}_l/\hat{a}_l > 0$, and if $\max\{\varepsilon_d, \sigma\} < 1$, then $\hat{x}_l/\hat{a}_l < 0$. If $\varepsilon_d > 1$ and $\sigma < 1$ or if $\varepsilon_d < 1$ and $\sigma > 1$ then, as $\theta_p = 1 - \theta_l$:

$$\theta_l\varepsilon_d + \theta_p\sigma - 1 > 0 \quad\Leftrightarrow\quad \theta_l(\varepsilon_d - \sigma) > 1 - \sigma \tag{2.73}$$

Hence, if $\varepsilon_d > 1$ and $\sigma < 1$, as $\varepsilon_d - \sigma > 0$:

$$\theta_l \varepsilon_d + \theta_p \sigma - 1 > 0 \quad \Leftrightarrow \quad \theta_l > \frac{1-\sigma}{\varepsilon_d - \sigma} (> 0) \tag{2.74}$$

and if $\varepsilon_d < 1$ and $\sigma > 1$, as $\varepsilon_d - \sigma < 0$:

$$\theta_l \varepsilon_d + \theta_p \sigma - 1 > 0 \quad \Leftrightarrow \quad \theta_l < \frac{\sigma - 1}{\sigma - \varepsilon_d} (< 1) \tag{2.75}$$

Q.E.D.

Substituting the expression of $\hat{x}_l$ from (2.71) in (2.68) yields the expression of $\hat{y}$:

$$\hat{y} = \frac{\theta_l \varepsilon_d (\varepsilon_l + 1)}{\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d \sigma} \hat{a}_l \tag{2.76}$$

which is positive if and only if $\hat{a}_l$ is.

Moreover,

$$\frac{\partial \hat{x}_l}{\partial \sigma} = \frac{\theta_p (\varepsilon_l + 1) \varepsilon_l}{(\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d)^2} \hat{a}_l \tag{2.77}$$

$$\frac{\partial \hat{x}_p}{\partial \sigma} = -\frac{\theta_l (1 + \varepsilon_l) (\varepsilon_l + \theta_l \varepsilon_d + \theta_p \varepsilon_d)}{(\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d)^2} \hat{a}_l \tag{2.78}$$

An increase in substitutability of factors σ when drought tolerant varieties are improved yields an increase in land use, and a decrease in pesticides use.

$$\frac{\partial |\hat{x}_l|}{\partial \varepsilon_l} = \frac{(\theta_p \sigma + \theta_l \varepsilon_d)}{(\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d)^2} |\theta_l \varepsilon_d + \theta_p \sigma - 1| \, |\hat{a}_l| \tag{2.79}$$

An increase in the elasticity of supply of land increases the magnitude of land surface extension or contraction.

$$\frac{\partial |\hat{x}_p|}{\partial \varepsilon_l} = \frac{\theta_l (\theta_p \sigma + \theta_l \varepsilon_d - 1)}{(\varepsilon_l + \theta_p \sigma + \theta_l \varepsilon_d)^2} |\varepsilon_d - \sigma| \, |\hat{a}_l| \tag{2.80}$$

The effect of an increase in land supply elasticity depends on the sign of $\theta_p \sigma + \theta_l \varepsilon_d - 1$ which, itself, determines the variation of land use when a land biased innovation is introduced.

Insect resistant varieties

Proof of proposition 3: Suppose that $\hat{a_p} > 0$ and $\hat{\alpha} = \hat{a_l} = 0$. Plugging this into (2.48), (2.49) and (2.50) yields:

$$\hat{x_p} = (\sigma - 1)\hat{a_p} + \left(1 + \frac{\sigma}{\varepsilon_l}\right)\hat{x_l} \tag{2.81}$$

$$\hat{x_l} = \hat{y} - \sigma\left(\frac{\hat{y}}{\varepsilon_d} + \frac{\hat{x_l}}{\varepsilon_l}\right) \tag{2.82}$$

$$-\frac{\hat{y}}{\varepsilon_d} = \theta_l\frac{\hat{x_l}}{\varepsilon_l} - \theta_p\hat{a_p} \tag{2.83}$$

From (2.83), we get the following expression for $\hat{y}$:

$$\hat{y} = \theta_p\varepsilon_d\hat{a_p} - \frac{\theta_l\varepsilon_d}{\varepsilon_l}\hat{x_l} \tag{2.84}$$

and simplifying (2.82) yields:

$$\hat{x_l}\left(1 + \frac{\sigma}{\varepsilon_l}\right) = \hat{y}\left(1 - \frac{\sigma}{\varepsilon_d}\right) \tag{2.85}$$

Substituting the expression of $\hat{y}$ from (2.83) in (2.82) yields:

$$\hat{x_l}\left(1 + \frac{\sigma}{\varepsilon_l}\right) = \left(\theta_p\varepsilon_d\hat{a_p} - \frac{\theta_l\varepsilon_d}{\varepsilon_l}\hat{x_l}\right)\left(1 - \frac{\sigma}{\varepsilon_d}\right) \tag{2.86}$$

Using the fact that $1 - \theta_l = \theta_p$ yields the relative variation in land use:

$$\hat{x_l} = \frac{\theta_p\varepsilon_l\left(\varepsilon_d - \sigma\right)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{a_p} \tag{2.87}$$

It is thus obvious that $\hat{x_l}/\hat{a_p}$ is positive if and only if $\varepsilon_d \geq \sigma$. Substituting this expression of $\hat{x_l}$ in (2.81) yields the following expression for $\hat{x_p}$:

$$\hat{x_p} = \frac{(\sigma - 1)(\varepsilon_l + \varepsilon_d) + \theta_p(\varepsilon_d - \sigma)(1 + \varepsilon_l)}{\varepsilon_l + \theta_p\sigma + \theta_l\varepsilon_d}\hat{a_p} \tag{2.88}$$

Suppose that $\sigma \geq 1$ and $\varepsilon_d \geq 1$. If $\varepsilon_d \geq \sigma$, it is obvious that $\hat{x_p} \geq 0$. Now suppose $\varepsilon_d < \sigma$. Then, as $\theta_p \leq 1$:

$$\begin{aligned}(\sigma-1)(\varepsilon_l+\varepsilon_d)+\theta_p(\varepsilon_d-\sigma)(1+\varepsilon_l) &\geq (\sigma-1)(\varepsilon_l+\varepsilon_d)+(\varepsilon_d-\sigma)(1+\varepsilon_l)\\ &\geq (\sigma+\varepsilon_l)(\varepsilon_d-1)\end{aligned}$$

which is positive as we assumed $\varepsilon_d \geq 1$. Moreover, from (2.88)

$$\hat{x_p}|_{\theta_p=1} = \frac{(\sigma+\varepsilon_d)(\varepsilon_d-1)}{\varepsilon_l+\sigma}\hat{a_p} \tag{2.89}$$

which is positive if and only if $\varepsilon_d \geq 1$ and

$$\hat{x_p}|_{\theta_p=0} = \frac{(\sigma-1)(\varepsilon_l+\varepsilon_d)}{\varepsilon_l+\theta_p\sigma+\theta_l\varepsilon_d}\hat{a_p} \tag{2.90}$$

which is positive if and only if $\sigma \geq 1$.

Q.E.D.

Substituting the expression of $\hat{x_l}$ from (2.87) in (2.84) yields the expression of $\hat{y}$:

$$\hat{y} = \frac{\theta_p\varepsilon_d\,(\varepsilon_l+\sigma)}{\varepsilon_l+\theta_p\sigma+\theta_l\varepsilon_d}\hat{a_p} \tag{2.91}$$

which is positive if and only if $\hat{a_p}$ is.

Moreover,

$$\frac{\partial\,|\hat{x_l}|}{\partial\varepsilon_l} = \frac{(\theta_p\sigma+\theta_l\varepsilon_d)}{(\varepsilon_l+\theta_p\sigma+\theta_l\varepsilon_d)^2}\theta_p\,|\varepsilon_d-\sigma|\,|\hat{a_p}| \tag{2.92}$$

Part II

Institutions for R&D on varieties

Chapter 3

Evolution of plant intellectual property protection regimes

Introduction

Innovation, the outcome of R&D process, is a particular form of information (Nordhaus, 1969). Indeed, innovation is merely a description of how to implement a process, or how to produce and commercialize a good or service. As any other form of information, it gathers several characteristics of a public good: it is neither rival (consuming information does reduce the total amount of available information) nor excludable (except when kept secret, information can hardly be reserved to a few users). Hence, in the absence of relevant institutions, regulations or interventions, a market equilibrium results in an under-provision of innovation. To overcome this market failure, one may think about two reasonable possibilities. The first one is a direct provision of innovation by the public sector. The second one is to create the legal institutions (or to develop adapted technologies) to overcome the public good characteristics of innovation. Both options have actually been adopted by governments. The wide development of public research institutes materialized the first option. Embodying the second option, intellectual property protection (IPP) systems have been widely implemented.

In this chapter, we review the existing intellectual property (IP) systems that protect innovations on agricultural varieties, their characteristics and the economic implications of their main features. IP rights are a central determinant of private research and development activities, and we saw in the previous chapter that private research has become a major component of innovation on plant varieties. Hence, understanding how private R&D on varieties is led, and its institutional framework, is necessary to study the environmental effects of crops innovations. This chapter aims to briefly present the arguments justifying the existence of IP systems, and at highlighting the particular features of innovation on varieties that justify the particularities of its IPP. It also intend to describe the types of institutional IPP available, namely *plant variety protections* and *full patents*, and to examine both their formal and effective differences. Following a general introduction on intellectual property protection, we present the two different IP regimes and review some aspects of their concrete implementation, and we finally review the existing literature on the economic impacts of the IP regimes over plant varieties.

1 Introduction to intellectual property protection

Intellectual property systems provide the holder of IP rights with the possibility to exclude its competitors from producing and commercializing the protected invention. As termed by Hopenhayn and Mitchell (2001), the IP holder is "given the right to exclude others from producing over a part of the product space". The major goal of IPP is dual: to encourage innovation, by ensuring innovators are rewarded for their activity, while promoting the disclosure of innovation, so that all actors of the economy can benefit from it (Gallini, 1992). The first component of such objective is clearly disposed by US Constitution: "To promote the Progress of Science and useful Arts, by securing for limited Times to Authors and Inventors the exclusive Right to their respective Writings and Discoveries".[1]

However, the two components of IPP's dual goal are contradictory, at least to some extent: if innovation is widespread among the economy and any actor can use it freely, it is unlikely that the innovator will be able to extract sufficient profit from its commercialization to be encouraged to innovate. To achieve these opposed objectives as efficiently as possible, IPP has to balance between the incentive for innovation that results from the monopoly rent granted to the IP holder, and maximized social efficiency, since the diffusion of the improved product of good at the largest scale

[1] Article 1, Section 8, Clause 8.

for the lowest price, *i.e.* the social optimum, is obtained under perfect competition.

1.1 From idea to IP

It is first useful to describe the different steps in the protection process, from the moment the idea of innovation emerges in the mind of its inventor, to the date the IPP expires. The following simplified description of these steps is based on Schoenhard (2008). For some types of invention or specific domestic laws, some of the following steps may actually be skipped or merged with some others.

1. Early idea of the invention. This step corresponds to the more or less vague idea, in the mind of the innovator, of a way to answer to a need or a problem by a product or a process.

2. Conception of the invention. This step is, in general, the first one to be legally recognized, and it is achieved when the inventor's idea is "sufficiently detailed that a person skilled in that area of technology could put the idea into practice without excessive experimentation" (Schoenhard, 2008, p. 570). The US case-law defines this moment as the "formation in the mind of the inventor, of a definite and permanent idea of the complete and operative invention, as it is hereafter to be applied in practice" (US Court of Appeals for the Federal Circuit, 1986).

3. Actual reduction to practice. Reduction to practice is the conversion of the conception to a more detailed description of the invention. A reduced innovation is generally the minimum requirement to apply for IP. In most cases, this step corresponds approximately to the realization of a working (eventually imperfect) prototype or a field test.[2]

4. IPP application. After constructive or actual reduction to practice, the innovator may file an IPP application before the relevant national IP office.

[2] The US Supreme Court (1888) explained that "The law does not require that a discoverer or inventor, in order to get a patent for a process, must have succeeded in bringing his art to the highest degree of perfection; it is enough if he describes his method with sufficient clearness and precision to enable those skilled in the matter to understand what the process is, and if he points out some practicable way of putting it into operation".

5. Publication of IPP application. After the application is filed, the IP office publishes the contain of the IP claim. Such step happens in general before the office formally acknowledges the application meets all the requirements to be protected.

6. IPP allowance. If all the requirements for the issuance of protection are met by the innovation and the IP claim, the IP office officially acknowledges and notifies the inventor that it will be granted the IP rights over its innovation.

7. IPP issuance. The IP office formally issues the protection. From the moment of IPP issuance, the innovator shall be fully entitled to avail itself of the rights associated to the protection.

8. IPP expiration. After the statutory protection period of IPP, at most, is elapsed, the IPP expires. IPP expiration may expire eventually earlier, if the protection holder does not renew it regularly (paying the renewal fees, in particular), as required by laws, or if it informs the IP office it abandons its rights. Any private right granted by IP protection ceases then, and the innovation becomes fully public.

Intellectual property protection provides an innovator with a series of rights over its innovation. These rights govern the relationships between the protected innovator an the adverse claimants, the government, and all the potential users of its innovation (Schoenhard, 2008). The extent of rights, as well as the timing of their evolutions throughout the different steps of the IPP process, are quite dependent on domestic regulations.

1.2 Requirements and rights associated to intellectual property protection

Several international initiatives have tried to encourage the convergence of intellectual property protection systems. For instance, the World Trade Organization (WTO) adopted, on its creation, the Trade-Related aspects of Intellectual Property rights (TRIPs) to harmonize patent regulations globally (cf *infra*). Despite these efforts of unification, IPP systems remain rather country-specific, and when different forms of IPP coexist within a country, the conditions to apply and granted rights vary across different IPP regimes (cf. *infra*). However, some features are rather widely spread across systems and/or countries, although some disparities may result from local case law interpretation of the extent of the treaties provisions. Innovations are generally required to have some utility or commercial value, and not to be obvious (which includes the novelty criterium). Applying to an IPP also implies the disclosure of the innovation characteristics and production process (a broadly adopted criterium is that the disclosure should provide enough details for any person, skilled in the art of the innovation sector, to be able to reproduce it).

Various characteristics are necessary to fully define the rights granted by an IPP regime, ranging from protection duration or scope to eventual exemption regimes (for research purpose or for some categories of actors), and most of them are quite heterogenous across countries. However, IPP most frequently grants exclusivity over the commercialization of the good to the first innovator or applicant (cf. infra) as long as the IPP is in force.

1.3 Timing of IP rights - First-to-file and first-to-invent - Prior user defense

As stated by Schoenhard (2008), two actions of an inventor are socially valuable, and thus “deserve reward: invention and public disclosure”. It would thus be legitimate to think that rights should be granted to the innovator separately, at both steps corresponding to these actions: first, when the innovation is conceived, and, second, when the IPP claim is published (as long as the invention meets the requirements of the IPP regime). In most countries, however, rights over innovation are granted altogether. In addition, they are granted to the first person to file the IP application (provided the IPP is subsequently granted). Such *first-to-file* regime is simple and straightforward to implement, and is built on the hypothesis that the first agent to file an IP claim on an innovation is very likely to have invented it. However, a *first-to-invent* regime has been implemented in some countries, and remained in force in the US until 2013. Such regime is not fully the logical traduction of the dichotomy of socially desirable actions previously mentioned, because rights are not granted separately to the innovator and the discloser. But the rights are not granted to the first IP claimer only either, as it is the case in the first-to-file regime. Instead, it is granted to the first IP claimer who can demonstrate it has actually been the first inventor of the innovation. In the US, such system had strong constitutional roots. Indeed, it obviously respected with more precision than a first-to-file system the mandate given by the "Patent and Copyright Clause" of the Constitution (Art. 1, §8, Cl. 8, quoted *supra*). In addition, a first-to-invent regime may prove fairer than a first-to-file one, because it protects better the most deserving inventors. Indeed, meeting the legal criteria for filing a patent is a difficult task, that requires time and specialized knowledge. In general, inventors are skilled in their technical field rather than IP law. A firm, that is not the most efficient inventor but with more skills in IPP claim filing may end up as the first-to-file firm, although another one was the first-to-invent one (Pritchard, 1995).[3]

In order to encourage disclosure as much as innovation, the rights granted by a first-to-invent regime are not absolute. They cease if the first inventor is proved to have "abandoned, suppressed or concealed the innovation".[4] Moreover, in the case the first inventor had not been the first to reduce its innovation to practice, it shall prove to have dedicated "reasonable diligence" to the reduction to practice of its innovation in order to claim its rights. "The man who first reduces an invention to practice is prima facie the first and true inventor, but [...] the man who first conceives, and, in a mental sense, first invents, a machine, art, or composition of matter, may date his patentable invention back to the time of its conception, if he connects the conception with its reduction to practice by reasonable diligence on his part, so that they are substantially one continuous act" (US Court of Appeals Sixth Circuit, 1893). In addition to the diligence provision, in order to avoid socially costly duplication of R&D effort and encourage an earliest public disclosure of the innovation, a first-to-invent system generally includes a limit of time between the moment the first inventor commercializes the innovation and the moment it applies for IP.[5] Without such provision, an inventor (especially if it already commercializes

[3]Suppose a firm or an individual inventor discovers an innovation. Because of lack of information or skilled lawyers, filing the IP claim may take some time to this inventor. Between the moment the first firm discovers and files the IP claim, another firm may discover the same innovation and, merely because it benefits from more experience or better skilled staff, it may finish the filing process before the genuine innovator. Of course, such case of "unfairness" of first-to-file system is limited to the cases where the first-to-file but not first-to-invent firm discovers the innovation truthfully. If it is convinced to have copied illegally the innovation, its IP will be cancelled and be granted to the "second-to-file" firm.

[4]35 U.S.C. §102 (g).

[5]Without such provision, a first innovator could simply commercialize its innovation, keeping secrecy over it, and wait for a second inventor to independently invent it. After such second discovery happens, the first inventor may claim that it actually invented it first, thus "coupling" the advantages of secrecy and IPP to extend as long as possible the exclusivity period.

a protected product on the market) may keep its innovation secret and wait for a competitor, who had subsequently discovered it, to release its innovation and claim for the protection rights. In the US, when the first-to-invent regime was enforced, this period used to be one year.[6]

However, the first-to-invent system has several weaknesses (Schoenhard, 2008). First, it may actually encourage more wasteful duplication of research than first-to-file regime. The latter provides a strong incentive to firms to file an IP claim (and thus to publicly announce they have found the innovation) as soon as possible when they have reduced their innovation to practice, because the threat that another competitor files the application before is strong. On the contrary, under first-to-invent regime, as long as the first innovator can prove it is still working on reduction to practice, there is no particular incentive to file quickly any application and, thus, to disclose the innovation: even if a later inventor files the claim, the first inventor who can prove it had kept working on reduction, will finally be granted the rights over the innovation. Second, for similar reasons, the first-to-invent regime may delay the public disclosure and, consequently, availability of the protected innovation. Third, the first-to-invent regime is also likely to lead to important cases of several firms claiming to have been the first inventor. Cases in this category are named *interferences*, and are often long and difficult to solve. Interferences are resolved by the patent office, which tries to find out which firm is the first inventor - some cases having taken more than a decade. Finally, a last argument against first-to-invent regime is that few countries adopted it. Understanding and exploiting this regime thus induced a cost for foreign firms. In 2011, the American Congress adopted the America Invents Acts (AIA) that, in 2013, changed the American first-to-invent regime to a first-to-file one.[7]

In a highly competitive R&D sector such as crops innovation, where similar innovations have often been reduced to practice almost simultaneously (within a few months) by several firms (cf. chapter 1), discussions on IP rights timing are

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[6] 35 U.S.C. §102 (b).

[7] However, the new act still includes a one-year grace period disposition. Such disposition allows an innovator to file a patent claim at most one year after having publicly disclosed (in another way than a patent claim) its innovation. Moreover, if an innovator A is the first to publicly discloses (by communication, commercialization, etc.) an innovation and files a patent application within one year after this disclosure, it will be granted the patent even if another independent innovator B files a patent application before firm A does so (and, of course, after firm A's public disclosure of the innovation).

highly relevant. For instance, the first patent granted over genetical engineered plants (concerning the use of *Agrobacterium tumefaciens* to ferry kamycin-resistance gene into plant cells) was filed simultaneously in 1983 by both Monsanto and the German Max Plank Society. While the European Patent Office granted the patent to the German institute, the US Patent Office declared an interference which has not been resolved before 2004, acknowledging Monsanto as the first inventor (Monsanto, 2004).

Another disposition related to innovation timing is the *prior user defense*. It may happen that two firms independently develop an innovation and start using and commercializing it (and even both intend to apply for IPP over it). In such situation, prior user rights is a provision of the IP law that allows both firms to use and commercialize the innovation, irrespective of which one is actually given the IP rights over the innovation (hence, prior user is a defense against infringement for the non IP rights owner). The existence and extent of prior user rights is very country specific, but several large economies such as France, Germany and the United Kingdom do offer such exemption to patent protection, eventually with some restrictions (USPTO, 2012).[8]. In the US, the AIA extended the scope of existing prior user rights[9]

2 Intellectual property protection on agricultural varieties

To study the drivers of innovation on agricultural varieties, it is important to get a perspective on the diversity of IPP regimes that are offered to plant breeders. Different regimes exist across countries, and even inside a given country, where different systems of IPP may coexist. Despite the heterogeneity of systems, it is universal that an IPP system is defined by two core characteristics: a finite duration (the period for which the protection is granted), and a given scope or breadth

[8]In Japan, Denmark, France, Germany and the UK, for instance, the independent invention must have been discovered faithfully before the filing of priority date of the patent application. For more details, see USPTO (2012).

[9]The AIA extends prior user rights to all technologies. It remains stricter than in many other countries, as the technology must have been used by the prior user right claimer at least one year before the public disclosure (either patent application or other ways) of the invention by the innovator that is granted a patent over it.

(the extent to which a substitutable good or process should be different from the protected one not to infringe the protection). Aside from these criteria, others may be part of the definition of an IP regime, but this varies across countries and types of protection.

2.1 Different intellectual property protection regimes

This section aims to provide general features about the different institutional IPP regimes available over plant varieties, coexisting (in most cases simultaneously) across countries, namely patents and plant variety protection. A comparison of these regimes *in abstracto*, independently from their effective domestic implementation, is made relevant to some extent because international treaties and convention set common characteristics these IPP regimes should meet, irrespective of the national context. Obviously, these conventions allow some latitude in the transposition of one of the IPP regimes in domestic law, and as noted by Koo et al. (2004), "countries are exploiting [the] degrees of freedom [provided by international conventions], presumably tailoring plant IP legislation to local circumstances". Hence, the stipulations of the conventions are minimum requirements, resulting for some features of IP systems in significant heterogeneity. Some of these national or regional specificities will be further discussed in section 2.2. It is remarkable, however, that institutional IPP over plant varieties is offered in many countries. Koo et al. (2004) surveyed plant intellectual property protection systems in 191 of the 208 countries classified by the World Bank. Although these figure have probably evolved since then, because new countries have joined the WTO and the UPOV (cf *infra*), they estimated that 91 of them, mainly high- and higher-middle-income ones, offered a statutory IP protection for plant breeders.

In order to suggest a first, general typology of IPP regimes, two major regimes are defined by international conventions, *full patents* and *plant variety protections* (also referred to as *plant breeders' rights* or *plant certificates*). These are the most common systems across the world. For members of the WTO, the TRIPs agreements have encouraged the convergence of national regulations of full patent protection. Treaties defining plant variety protections (PVPs) are quite precise and have developed homogenous systems across countries. Thus, this regime of protection is the most uniform across countries - although a few countries, such as India, have exploited as much as possible the latitude offered by the treaties to develop a more *sui generis* regime.[10] Secrecy is another intensively used alternative to formal IP, especially by hybrid breeders, based on legal roots as well. Nevertheless, because of scarcer international treaties on this topic, national regulations have more freedom to define the rules of secrecy regimes, and universal features are more difficult to identify. Finally, aside from these regimes set by law, other IPP mechanisms co-exist as alternative to institutional protection. One may think about contractual provisions, or technological mechanisms are also available (like genetic use restriction technologies - GURTs - such as the "terminator" gene), although their detailed description is beyond the scope of the present study.

Full patent

Patents are the most common tool of intellectual property protection worldwide. They are generally quite country specific, because they most often result from a long national history of rule of law.[11] This makes it difficult to provide extensive universal features about full patent regimes. In particular, whether agricultural innovation can be protected by a patent depends on the country where protection is looked for (see *infra*, section 2.2). This is notwithstanding a general trend, at least in developed countries, initiated in 1980 in the US and in the late 1990s in Europe, that tends to recognize more easily the patentability of living organisms. However, several characteristics of patents are quite constant across countries - in particular those included in the annex 1C to the Marrakesh Agreement Establishing the WTO, usually named "TRIPs", which defines the minimum requirements patent systems in the WTO member countries should meet.

A patent may protect either a product or a process, provided such invention is new, not obvious ("involve an inventive step") and useful ("capable of industrial application") (World Trade Organization, 1994). The objective of patent protection, as claimed by the 7th article of the TRIPs agreement, is to "contribute to the promotion of technological innovation and to the transfer and dissemination of technology, to the mutual advantage of producers and users of technological knowledge and in a manner conducive to social and economic welfare, and to a balance of rights and

[10] India's regime is briefly discussed in section 2.2.

[11] For instance, in France, IPP is a provision of the 1787 Constitution: the king of France granted special rights to innovators through *lettres de patente*.

obligations". TRIPs hence acknowledge the necessary balance between incentive for innovation, and diffusion of technology. In general, a patent grants large and strong rights over the patented innovation to its owner who holds the exclusivity over its production, trade and, frequently, its use for research and development purposes. In article 30, the TRIPs agreement stipulates that "members may provide limited exceptions to the exclusive rights conferred by a patent, provided that such exceptions do not unreasonably conflict with a normal exploitation of the patent and do not unreasonably prejudice the legitimate interests of the patent owner, taking account of the legitimate interests of third parties". However, as noted by Jördens (2002), no further precision is provided by the TRIPs agreement about the boundaries of such exceptions, that are left for definition to national regulations and case law. Although the patentee holds exclusivity over the use of its invention for any purpose, an important characteristic of a national patent regulation is whether a patent infringement should be recognized when a third-party innovators use the patented good or process to develop new products or processes without agreement from the patentee. This point has important economic implications on various issues, from incentive to innovate to social value of innovation. Whether, and the extent to which such "experimental use exemption" is accepted depends largely on national patent systems. The United Kingdom's patent law is among the loosest, and Article 60 (5) (b) of the British Patent Act states that "an act which [would otherwise] constitute an infringement of a patent for an invention shall not do so if [...] it is done for experimental purposes relating to the subject-matter of the invention [...]". On the contrary, the US case law has adopted a rather restrictive position on experimental use exemption (cf section 2.2).

The case of living organisms patentability has been a burning questions, for various reasons, and notably ethical considerations, since the 1960s. Article 30 of the TRIPs agreements acknowledges the specificities of living organisms regarding intellectual property protection. They allow the member States to exclude from patentability "plants and animals other than micro-organisms, and essentially biological processes for the production of plants or animals other than non-biological and microbiological processes. However, Members shall provide for the protection of plant varieties either by patents or by an effective *sui generis* system or by any combination thereof". This provision has allowed the majority of WTO members to implement an alternative system to patents for plants varieties - in most cases, Plant Variety Protection.

Plant variety protection

Plant variety protection (PVP) designates a *sui generis* regime of intellectual property protection that has been specifically designed for plants, distinct from patents. It has been developed by the UPOV, and is available to all the nationals of the parties of the Convention of the International Union for the Protection of New Varieties of Plants, or UPOV (*Union internationale pour la Protection des Obtentions Végétales*, in French). While patents are historically designed *ad hoc* by each country and eventually converged later among the parties of international treaties on the topic in a "bottom-up" movement, PVPs have been implemented following a "top-down" approach. The main features of PVP are set by an international conventions and only implementation details are left to the parties' national policy. The first Convention of the UPOV has been adopted in 1961. As of October 2015, the Convention gathered 74 members, and was hence enforced in 93 countries, including all the European Union member States, and the United States (UPOV, 2015).[12] Except, eventually, for a temporary period following the signature of a new party (UPOV, 1991, article 3), any national from one of the parties to the Convention that has been granted a PVP in any of them, is protected in every party State (UPOV, 1991, article 4). The intellectual property protection offered by PVPs is generally presented as weaker than the one offered by full patents, due to 3 specificities: farmer's exception, breeder's exemptions and, eventually, farmer's privilege, described hereafter.

To apply for a PVP, a breeder must have "discovered and developed" (UPOV, 1991, article 1) a variety that is, simultaneously:

- New. The variety must not have been sold or propagated in any territory (either of a member or a non member State) before the claim of the protection (UPOV, 1991, article 6).
- Distinct from other varieties. The variety must be "clearly distinguishable from any other variety" protected or not (UPOV, 1991, article 7). This criteria is probably the most difficult to appreciate, and has hence been further specified

[12]Among the 74 members are the African Intellectual Property Organization since July 2014, which gathers 17 countries, none of which is a party of the UPOV under its own name, and the European Union since July 2005, which gathers 28 countries of which 24 were already parties in their own names and that are hence counted among the 74 members.

by case law, causing some heterogeneity across countries. It is also useful to note that distinction is a weaker condition than non-obviousness, which is required by most patent systems.

- Uniform. The "relevant characteristics" of the variety must be sufficiently uniform among the different plants of the variety (UPOV, 1991, article 8).

- Stable. The variety must keep its "relevant characteristics" throughout the protection period (UPOV, 1991, article 9). Most patent systems require a written description of the invention that allows to reproduce it. This is not the case for PVPs, which impose the weaker condition that the protected variety is stable when reproduced from existing plants. This criteria raises the question of whether hybrid varieties may be considered as varieties, because the characteristics of hybrids generally vanish in the second generation, and, hence, could be protected by a PVP. In the US, the Plant Variety Patent Act (PVPA) allows first generation hybrids to be protected as a plant variety since its 1994 amendment. In Europe, the debate is more alive: although the Community Plant Variety Office recognizes hybrids as plant varieties (Kiewiet, 2011), the European Patent Office has judged it is not, due their lack of "suitability from being propagated unchanged" (EPO BoA, 2008, Reasons for the decision, 3.).

It should be noted that, contrary to most full patent systems, the UPOV Convention does not mandate varieties to be useful, from any point of view.

Every party of the UPOV may decide the duration for which a PVP provides intellectual property protection to its holder. However, the PVP protection should not be shorter than 25 years for trees and vines, and 20 years for all other plants (UPOV, 1991, article 19). Once a variety is protected by a PVP, this protection extends actually beyond the variety *stricto sensu*: it applies, as well, to varieties "whose production requires the repeated use of", "which are not clearly distinguishable [...] from" or "which are essentially derived from" the protected variety (UPOV, 1991, article 14, (5) (a)). The first two criteria are clear in themselves, but the last one desserves further precisions (cf *infra*).

The Convention sets two compulsory (UPOV, 1991, article 15 (1)) and one optional (UPOV, 1991, article 15 (2)) exception to the a breeder's full property over its invention. Practically, within the scope of these exceptions, anyone can produce, stock, use and, when applicable, sell, import and export its production without paying royalties to, or agreeing on any authorization from the protected breeder. The first compulsory exception, named the *farmer's exception*, allows a farmer to use freely a protected variety for *private* and *non-commercial purpose.* The most common example for this exception is subsistence farming. Farmers are allowed to replant a share of their harvest for the purpose of their own consumption. The second compulsory exception, named the *breeder's exemption*, allows any breeder to conduct any form of experimentation on protected varieties, as well as "any acts done for the purpose of breeding other varieties and, for the purpose of exploiting these new varieties provided the new variety is not a variety *essentially derived* from another variety". Compared to patents, the compromise between innovation incentives and knowledge diffusion under PVP, accounting for the breeder's exemption, thus grants more weight to knowledge diffusion: as long as a new variety derived from a protected variety is not essentially derived (ED), the owner of the protection over the original variety has no right over the new one. Last, the Convention stipulates that "within reasonable limits and subject to the safeguarding of the legitimate interests of the breeder", the parties may allow their nationals to replant the product of their harvest and dispose of it, either freely or under favorable conditions. In France, for instance, the law of 8th December 2011, which transposes the Convention (France, 2011) sets, for 34 varieties protected by a PVP[13] the royalties that should be paid by the farmers to the protected breeder in order to replant their harvest and dispose of the product as they wish.[14]

The Convention defines (UPOV, 1991, article 14, (5) (b)) an "essentially derived" variety as a variety that is "predominantly derived from the initial variety[...] while retaining the expression of the essential characteristics that result from the genotype or combination of genotypes of the initial variety", and "clearly distinguishable from the initial variety".[15] Moreover, "except from the differences which result from the act of derivation, it conforms to the initial variety in the expres-

[13]The list of 21 of these varieties is set by the European Council regulation no2100/94, (European Community, 1994, Page 8/38), completed for the 13 remaining varieties by the law's *décret d'application.* (France, 2014, article 1)

[14]Of course, even when this stipulation of the Convention is not activated for a given variety, the farmers may negotiate with the breeder the right to replant their harvest, and to agree on a royalty to do so. But in this case, the breeder may refuse, and whenever it agrees, the royalty amount is set by the negotiation. The activation of this stipulation obliges the breeder to accept, for a royalty that is set by the State - in general at a level that is more favorable to the farmers than what would have been the result of negotiation.

[15]If it is not "clearly distinguishable from the initial variety", then it is protected by the PVP, no matter whether it is ED.

sion of the essential characteristics that result from the genotype or combination of genotype of the initial variety". Finally, the Convention provides examples (UPOV, 1991, article 14, (5) (a)) of how an ED variety could be obtained: by "the selection of a natural or induced mutant, or of a somaclonal variant", "the selection of variant individual from plants of the initial variety", "backcrossing" or "transformation by genetic engineering". In order to define more precisely the notion of "essential characteristics", the breeding industry has agreed on norms (Roberts, 2002), and the UPOV has published an explanatory note about it in 2009 (UPOV, 2009). Moreover, the reason why essentially derived varieties have been added to the scope of a PVPs helps to understand the extent of such concept (Jördens, 2002). Before 1991, ED varieties were not mentioned in the UPOV Convention. The development of patentable biotechnologies, and the possibility to introduce them into plants covered by a PVP, created an imbalance between the holder of a patent over a genetic innovation, and the holder of a PVP. Indeed, without the extension of PVP to ED varieties, suppose the patent holder of a genetic innovation creates a variety B by the introduction of its genetic innovation into a variety A, initially developed by the breeder. The patentee would not have to pay any royalty to the PVP holder, because it would fall under the breeder's exemption. If, in turn, the PVP holder creates the same variety B, it will have to pay a royalty to the patent holder. In that case, the variety B is essentially derived from the variety A. The 1991 act of the Convention hence extended the breeder's rights to restore the balance between patents and PVPs holders.[16] Thus, the notion of essentially derived varieties appears clearly as an exception to the breeder's exemption (Roberts, 2002).

Article 17 of the Convention, finally, allows contracting parties to restrict the breeder's rights for public interest, as long as the breeder receives an "equitable" compensation.

Coexistence of patents and PVPs

Conflicts between patents and PVPs may arise in two situations: when the plant is protected by a PVP and either the process to obtain it or an element of it is protected by a full patent, and when a claim is filed by a breeder for both systems

[16] It is still possible for the patent holder to develop variety B without owing any royalty to the breeder - the extension of PVPs to essentially derived varieties only restricts commercialization - whereas it is still impossible for the breeder to do so without the agreement of the patent holder.

simultaneously, on a single plant. It is broadly the case that when a non-essentially biological process[17] or a DNA sequence is covered by a patent and inserted and expressed in a plant, the patent extends to the plant.[18] It is also often possible for a plant itself to be protected by both a PVP and a patent. Before 1991, the UPOV Convention clearly stated that PVP protection of a plant was exclusive of patent protection, but the 1991 revision of the UPOV withdrew such provision.[19] Hence, provided that no national dispositions forbid it, the UPOV allows a new variety to be protected by both a patent and a PVP. The US Supreme Court (2001) and the European Patent Office (EPO EBoA, 1999b) have both agreed on this possibility, ruling that a plant could be protected by both a utility patent and a PVP (in countries where patentability of living organisms is allowed).

This possible overlapping of patents and PVP can restrict significantly the provisions of each system. Indeed, for instance, breeder's exemption will not be recognized for a plant protected by a PVP and a patent (Moufang, 2002). The US Court of Appeals for the Federal Circuit (2002b) has stated that the "right to save seeds of plants registered under the PVPA does not impact the [absence of] right to save seed of plants patented under the Patent Act".

Trade secret

Trade secret is a way of IPP *per se*, as long as the innovator is able to keep its innovation secret, and is most often regulated by national rules. However, even more than for patents, trade secret protection laws differ from a country to another. Nevertheless, some general dispositions (concerning the definition of secrecy, the legal ways for a third party to break secrecy, etc.) are rather common. In particular the definition of a trade secret often requires that it may derive an economic value. For secrecy over an innovation to be recognized, the innovator is generally required to have taken reasonable measures to keep relevant information secret. A competitor should only break secrets by fair and faithful means. The scope of "relevant

[17] Essentially biological processes are generally excluded from patentability.

[18] For instance, in the European Union, these provisions are set, respectively, by articles 8 and 9 of the "Biotech Directive" 98/44/EC.

[19] This provision stipulated that "each member State of the Inion may recognize the right of the breeder [...] by the grant of either of a special title or a patent. Nevertheless, [when protection is available] under both these forms may provide only one of them for one and the same botanical genus or species".

measures" and "fair and faithful means" however depends on national regulations and case-law. Trade secrets have been a particularly useful intellectual property protection concerning hybrids. Almost all the value of the hybrids is conditional on its breeder's capacity to keep secret the parents varieties from which the variety is derived (Roberts, 2002). For instance, in the case Pioneer Hi-bred v. Holden, the secret inbred parental lines of of of Pioneer Hi-Bred's hybrid have been regognized as misappropriated by Holden Foundation Seeds, Inc. (US Court of Appeals Eigth Circuit, 1994).

2.2 Exemples of agricultural IPR implementation

The current section provides a brief presentation of institutional IP regimes available in some important areas for varieties innovation.

In the United States[20]

Three intellectual property systems are available for plants in the United States: two types of patents on the one hand, and plant variety protection certificates on the other hand. A general feature of the American IP system over plant is that it has been more and more popular: according to Pardey et al. (2013), 42% of IP rights granted over the period 1930-2008 have been granted between 2000 and 2008.[21]

Plant patents (for asexually reproduced plants only). The Plant Patent Act (PPA) of 1930 acknowledges that a new variety of plant is a discovery and that its breeder should be granted a patent over it if requiring so. Due to the the large variability of sexually reproduced plant by that time, these were hardly identically reproducible.[22] Granting a "usual" patent to the inventors of varieties belonging to this type of plants was thus uncertain. Consequently, the 1930 PPA allowed

[20]For a deep historical perspective on plants IPR in the US, see Kevles (2002).

[21]This is probably explained by the fact that the IP rights granted over biotechnology techniques in the 1990s were individually of much higher potential value - as they were the basis for the widespread of these technologies - but not as numerous as those that have been granted over the declination of bioengineered varieties that breeders developed in the 2000s.

[22]"Sexually reproduced plants" designates plants that require to be pollinated to produce seeds. As for animals, they hence mix genes from a mother and a father, and if both are not from the same variety - although even in that case genetic mutations may occur -, the seeds can drift rather far away from the original characteristics of each of the parent plants.

plant patents for asexually reproduced plants only, excluding tuber-propagated ones. Hence, between 2000 and 2008, 78% of varieties protected by plant patents have been ornamental plants, and 19% have been fruits (Pardey et al., 2013). According to Kevles (2002), despite rather weak disclosure requirements,[23] the protection conferred to breeders by plant patents were quite narrow, and "in practice, the Plant Patent Act only prevented unauthorized advertising by the patented name. It functioned more as a registration system than as the kind of rigorous examination and screening system characteristic for industrial inventions [...]. All that the breeders really got from the act was the ability to use a tradename and a legal basis for infringement suits". It should be noted, however, that the US Court of Appeals for the Federal Circuit (1995), weakened the plant patent system. Indeed, it ruled that any derivation from a plant patent protected crop, by other means than asexual reproduction, would not infringe the plant patent. This opened a large way for breeders to use almost freely plants that reproduce both sexually and asexually. Despite these weaknesses, the largest share (almost 60% in 2008) of the flow of IPP over plant varieties granted in the US are plant patents (Pardey et al., 2013).

Plant Variety Protection (for sexually reproduced plants only). The Plant Variety Protection Act has been adopted by American Congress in 1970 and provides intellectual property protection for sexually reproduced and tuber propagated plants only (protected by the PPA, asexually reproduced plants are excluded from plant variety protection). Appart from this restriction, the American PVPA meets the requirements set by the UPOV Convention described in section 2.1. The UPOV does not explicitly set minimum rules governing the elements that should be disclosed in a PVP claim, and the US have adopted rather weak criteria, especially compared to disclosure requirements of utility patents (Alston and Venner, 2002).[24] Similarly, because the possibility to sell freely protected seeds saved by farmers is not strictly regulated by the UPOV, and the member States' appreciation is large on this topic, the rules of such activity with seeds protected by PVP in the US have varied. Until a

[23]"The act called for the submission of a color painting or photograph as well as a written description of the plant that was as 'complete as is reasonably possible'. It called for an historical preamble describing how the plant was bred or where the sports from which it was asexually reproduced had been found, and how it differed from the plants that comprised its pedigree. It asked for data concerning when the plant bloomed and which soils and climates best suited it. It expected a technical description outlining the color and shape of the bush, leaves, and flower".

[24]The PVPA (7 U.S.C. 2422, §52) only requires "a description of the genealogy and breeding procedure, when known.

1995 Supreme Court decision, such possibility was widely open to farmers. However, it has been limited much more limited since then, and is essentially reduced to the minimal possibility for farmers to replant on their own land their saved seeds (Fuglie et al., 1996). Covering sexually reproduced plants, PVP obviously protects a much wider spectrum of plant types than plant patents: 29% of PVP certificates protect cereals, 20% oilseeds, 20% vegetables, 12% grasses and 6% fiber crops, over the 2000-2008 period (Pardey et al., 2013). PVP rights represent roughly 20% of IPP over plants granted each year in the US (Pardey et al., 2013).

Utility patents. Patents in the United States are governed by the 1952 Patent Act, which states that "whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefor [...]". Before the 1970s, the question had never been raised of patentability of life. Indeed, no human invention (that met the non obviousness criteria) involved living organisms before the first works on biotechnologies. Hence, though it was clear utility patents could be attributed to processes implemented to produce plants, no patent application had been filed for a living organism *per se* and whether this was possible had remained a pending question.[25] The first case had to be decided when, in 1972, Ananda Chakrabarty applied for a utility patent over a bacterium that was able to consume oil slicks, and filed a patent application to protect his invention. In the *Diamond v. Chakrabarty* decision, the US Supreme Court (1980) acknowledged that, as long as a living organism met the criteria of patentability, it could be granted a utility patent. Under the utility patent regime in the US, a very narrow experimental use exception exists, established by the US Courts case-law (Henson-Apollonio, 2002), which has been restricted even further in 2002. Before 2002, the case law did not qualify as patent infringement research led on a patented innovation, as long as it was not done for commercial purpose. In the Madey v. Duke University case, the US Court of Appeals for the Federal Circuit (2002a) decided that research could not be conducted on any patent protected invention, "in keeping with the alleged infringer's legitimate business".[26]

[25] Actually, according to Kevles (2002), most lawyers would have thought it was not.

[26] The case concerned a university that was conducting experiments on patented material, strictly as a mere training for its students, without searching any further innovation. Considering that the "legitimate business" of a university is to attract students and that proposing training on this material was a way to attract students, the Court decided that this activity should be regarded as a patent infringement.

Hence, in the US, an experimental exception still exists, though restricted to non-commercial purpose, in a very strict acception. Finally, most utility patents (46%) granted over plant in the US for the 2000-2008 period protect corn, followed by soybeans (38%) and vegetables (5%). The remaining 20% of IPP over plants granted in 2008 were utility patents.

In the European Union

Regulation in the European Union States results from both European law and national laws. Because acts adopted by the Union may allow some limited flexibility in transposition in national law, a few differences may occur from one state to another (for example, UK research exception is broader than it is on average in the EU). This section hence reviews relevant norms applicable in the whole EU, keeping in mind that slight variations across European countries may occur. The European Union, and all its member States, are members of the UPOV, so PVPs are available, over any kind of plant, in any European country without much significant heterogeneity across the Union.

Since 1973 and the adoption of the European Patent Convention (EPC), the European Patent Organization (EPO),[27] has prohibited patenting a plant variety (European Patent Organization, 2000, article 53): "European patents shall not be granted in respect of: (a) inventions the commercial exploitation of which would be contrary to 'ordre public' or morality [...] (b) plant or animal varieties or essentially biological processes for the production of plants or animals; this provision shall not apply to microbiological processes or the products thereof; [...]". Point (b) of article 53 has been adopted to leave to plant variety protection as the only intellectual property protection system for plants (Kevles, 2002).

However, in 1998, the European Union has adopted the "Biotech Directive". In its article 4, this directive reaffirms that "shall not be patentable: plants and animal varieties; essentially biological processes for the production of plants and animals". However, it also sets limits to this prescription, and enlarges as well the previous scope of patentable life innovations in two directions. First, inventions can be patented as long as they do not concern a single plant variety (paragraph 2).

[27]EPO member States include, among others, the European Union States, Iceland, Norway and Turkey

Second, "microbiological or other technical process or a product obtained by such process" can be patented even if it is an essentially biological process (European Community, 1998). Considering the restrictions to further plant breeding or inventions caused by overlapping PVP and patent protection, as explained in section 2.1, the Biotech Directive allowed breeders and patent claimers, who develop a plant or invention that requires to infringe a patent or a PVP, to apply for compulsory licences (article 12) "subject to payment of an appropriate royalty", as long as they have unsuccessfully tried to negotiate a contractual licence. It should be noted that article 12 does not mention the use of patented material in the breeding process, as it "presupposes the very existence of the new plant variety" (Moufang, 2002).

Moreover, the European Patent Office, which enforces the EPC, and especially its Enlarged Board of Appeal (which judges cases regarding patents granted by the office), has adopted a very tight and restrictive interpretation of the exceptions to patentability from 1999 on. Adopting a point of view similar to the European directive 98/44's one, it decided that article 53 (b) of the Convention should be interpreted as not forbidding a patent over any invention which application is not restricted to a single plant variety. The Board stated that "a claim wherein specific plant varieties are not individually claimed is not excluded from patentability under Article 53(b) EPC, even though it may embrace plant varieties" (EPO EBoA, 1999a). Furthermore, in a decision of 25th March 2015 "Tomato II", it ruled that a plant material, such as a fruit - which is not a "plant variety" *stricto sensu* -, can be patented, even if it is obtained through an essentially biological process (EPO EBoA, 2015). Hence, the traditional vision that patents over plants shall strictly not be granted in Europe has been challenged recently, and is quite likely to be challenged again in the future.

As mentioned in the introduction to this section, the question of research exemption under patents in Europe is state-dependent. On average, however, a research exemption exists in Europe, and it is more tolerant than its US counterpart.

In India, a different *sui generis* form of protection

The case of Indian IPP over plant varieties is interesting because it provides a much weaker protection for breeders than what exists in other countries. Before 2001, IPP in India was provided only based on the Indian Patent Act of 1970, which excluded plants and agriculture methods from patentability. In 1994, India signed the TRIPs agreement, and to comply with it, it adopted in 2001 the Protection of Plant Varieties and Farmers' Rights Act (PPVFRA), which sets a *sui generis* IPR for plants (Brahmi et al., 2004). The PPVFRA is built extensively on plant variety protection schemes, albeit with significant differences. To apply for protection, a variety should meet the same criteria of novelty, distinctiveness, uniformity and stability (India, 2001, Article 15). The most significant differences with the "average" PVP regime are as follows.

- Although their existence is expressly recognized by the act, essentially derived varieties can be protected similarly to other varieties (Article 23).
- A provision for "benefit sharing" is included in the act (Article 26). It prescribes that the authority in charge of plant protection should "invite claims of benefit sharing to the variety registered" during a given period. Thus, any Indian person, group of person, including farmers, firms, governmental and non-governmental organization, considering itself as a contributor of the plant development, may claim a share of the benefits driven by its commercialization. The share of benefits accruing to each party is decided by the authority after hearing all of them.
- Varieties including genetic use restriction technology (GURTs, such as the "Terminator" gene) are expressly excluded from protection (Article 29, (3)).
- Farmers have more extended rights than those conferred by plant variety protections: not only can they sow seeds from their farms for their own consumption, they can, as well, "save, [...] exchange, share and sell his farm produce including seed of a variety protected by" the PPVFRA, as long as the seeds are not sold in a package indicating it is of a protected variety (Article 39, (1), (iv)), this is the sold seeds should not be branded.
- After three years from the date of issue of the protection, compulsory licences can be claimed by anyone and may be granted by the authority in charge of plant protection under certain conditions, especially if "the variety is not available to the public at a reasonable price" (Article 47).

The provisions of the PPVFRA appear clearly to weaken the rights of breeders, compared to standard regimes of PVP. As summarized by Koo et al. (2004), the

PPVFRA "seems to heavily favor 'public' over 'private' interests". The Indian case will probably be an interesting one to study empirically the consequences of weaker regimes of intellectual property on R&D activity.

3 The influence of the intellectual property protection regime on the agricultural R&D market

The regime of intellectual property aims to tune the market power of the innovator in order to balance market efficiency and incentive to innovate. It has thus has an immediate impact on the innovation market. Qaim and Traxler (2005) provided a comparison between the US and Argentine markets for improved varieties, which exemplifies the consequences of different strengths of intellectual property regimes. While, in the US, Roundup Ready soybeans are protected by a full patent, in Argentina it is protected by a rather permissive PVP system. In particular, Argentine farmers are allowed to save and replant seeds from their harvests, which represents 30% of total planted seeds. Moreover, black market seeds appear to be quite common in Argentina, and accounts for 35% of soybeans grown seeds. Only the remaining 35% are bought directly by farmers from certified sellers. Qaim and Traxler stated that such difference in IP regime strength is responsible for the 43% more expensive seeds in the US than in Argentina.

The efficacy of IPP regimes (*i.e.* their capacity to reach the goals, set by policymakers, why they have been implemented) has been the subject of an important empirical literature. Most of this literature has focused on the extent to which IP protection actually encouraged research and development. Early works on the effect of PVPA in the US on the emergence of new varieties of different crops (cotton, soybeans, wheat) did not conclude to a clearcut answer to this question (Babcock and Foster, 1991). The first estimates of the impact of PVPA on public investment in research did not bring clear answer either (Knudson and Pray, 1991). The correlation between the implementation of PVPA in 1970 and the subsequent development of private research on varieties are not linked by a causality relationship, since the latter might have result from a sharp increase in demand for output. It is certain that the development of IPP over plants has triggered a stronger R&D effort from breeders. But this observation is not sufficient to justify the existence of IPP regimes over plants, as an increase in private R&D expenses that do not result in more socially desirable varieties would be pointless. The impact of IPP on plants characteristics is thus much more relevant to study than its impact on mere private R&D effort.

Alston and Venner (2002) estimated the effect of PVPA on increases in wheat yields in the US, over the period 1950-1994. They concluded that the PVPA had no significant positive consequences on wheat yields.[28] They explained that should PVP have a positive influence on yields, the estimate of the coefficient of the latter variable should be positive and significant, which is not the case. However, their regression was flawed in several respects. First, the effect of PVPs on yields, if it exists, would be lagged.[29] Second, and more importantly, endogeneity issues are not negligible in their model, to say the least, but were not treated properly.[30] In the second set of estimates, they regressed experimental wheat yields on several variables. [31] They found insignificant negative effect of the PVP wheat yield, providing a more convincing argument against the idea that IPP over plants trigger increases in yields.[32]

Taking into account the multicolinearity issues in Alston and Venner, Kolady and Lesser (2009) ran a comparable analysis, which leads to different results.[33] They

[28]Alston and Venner (2002) ran two sets of estimates. In the first one, they regressed commercially available wheat yields on various variables, including planted acres and the share of acres planted with PVP protected varieties.

[29]If a large share of cultivated area is planted with protected varieties in year t, it will encourage breeders to invest an R&D effort on this year, which will result in increased yields 6 to 12 years later. The authors treat this phenomenon with a dummy variable that is equal to 0 until 6 years after the adoption of the PVPA, and to 1 afterwards. It would have been probably more efficient to use lagged variables (*e.g.* to regress the wheat yields on year t over the share of PVP protected acres 6 years before).

[30]Indeed, the share of land planted with protected varieties is likely to be determined strongly by the yields of such varieties. The same issue arises with total cultivated area: the higher wheat yields, the more profitable cultivation and hence the wider cultivated area.

[31]The explicative variables included the year of harvest, one dummy variable equal to 1 if the variety has been developed by a private breeding program, and another one equal to 1 if the variety is protected by a PVP.

[32]However, it should be noted that the estimated coefficient of the private breeding program dummy was both positive and significant, mitigating the authors' conclusions. Indeed, since IPP has triggered private investment in R&D on plant varieties, a plant is all the more likely to be developed under a private program that it is protected by a form of IP, so the "private" dummy variable may well capture some of the "PVP" variable effect. For the same reason, it is most probable that introducing this variable and the PVP dummy causes multicolinearity in the model, weakening its conclusions.

[33]To treat the multicolinearity problem identified in Alston and Venner, they ran two different sets of regressions, each one including either the private variety dummy or the PVP variable.

only considered field trials as the dependent variable. [34] They also did not use the absolute yields of wheat as the dependent variable, but rather used the relative yields compared to the yield of a reference variety. They found a positive and significant effect of both private varieties and protected varieties on crops yields, and hence concluded that IPP causes the development of varieties with higher yields. However, they did not treat the problem of endogeneity.[35] Moreover, a risk of overfitting the model is driven by the numerous dummies (one for each year between 1975 and 2006) included by the authors. Finally, as noted by Thomson (2014), public and private research on plants may not have the same targets. Each of them may aim to develop varieties with other characteristics than yields. Hence, the fact that private sector varieties' yields are higher than public sector's ones may not result from stronger effort of the private sector due to PVP, but rather to the segmentation of the market.

It is quite a restrictive assumption to consider that only yields are the main outcome of research. Breeders may indeed focus on other outcomes for research: quality of the output, resistance to pests and diseases, lower needs for input, resistance to droughts, etc. Thomson (2014) enhanced the previous analyses of IPP impact on wheat varieties value by building a dependent variable that includes output quality and diseases control costs. His estimation focused on Australia, benefitting from the implementation of PVP rights in 1994. Contrary to previous studies, he used neither commercial adoption of varieties by farmers (stating that this variable captures other elements than crops performances, such as advertisement, marketing, etc.), nor field trials (which are too specific, as actual land conditions may be very heterogenous, and different from field trial ones). Instead, he simulated (based on random trials across Australia) what the productivity of the new varieties would have been if they had been widely adopted in each region of observation. Despite a careful econometric model, Thomson did not fully treat the endogeneity issue highlighted above. He found that the introduction of PVP has reduced the productivity of varieties released by plant breeders. Supported by interviews of managers from the breeding sector, he stated that such phenomenon has two main causes: a gen-

[34] On the contrary, Alston and Venner ran two different estimations, on both commercial use and field trials.

[35] Because protection is costly, independently from the sector (private or public) that develops them, new varieties are likely to be protected by PVP only if their breeders expect high yields in the development process. Similarly, private firms are likely to release for field trials only the varieties that show the highest yields among those they have developed.

eral decline in research spillovers (because of a more difficult access to protected germplasm than to the publicly developed one), and the capacity of private breeders to commercialize protected varieties even when they do not outperform available ones.

More generally, the influence of the IPP regime on the quality of research output (be it yields or productivity in a more general acception) is only one aspect of the influence of IPP on R&D. It is also interesting to consider whether policy choices in IPP regimes actually change the direction of R&D, *i.e.* sectors and subsectors that are targeted by the breeders. This issue is particularly relevant regarding agricultural innovation on varieties, because crops improvement are generally quite country-specific. Thus, if IPP regime design actually encourages research in some sectors and can be detrimental to other sectors, it would be more difficult to "import" innovation in the neglected sectors of agricultural than in others. Fewer authors have studied IPP regime impact on research directions than those that focused on overall research effort. Moser (2005) showed that the absence of proper IPP regimes tends to drive private R&D towards innovations that cannot be easily replicated, or can be protected by other means.[36] Although she did not focus on agricultural varieties at all, her results provided interesting insights for the agricultural case. Indeed, such finding is consistent with the observed focus of private R&D on hybrids in the beginning of the 20th century: when IPP over plants did not exist, private innovators concentrated their efforts on sectors where appropriation alternatives existed. It also makes clear for policymakers that, on varieties that cannot offer alternatives to IPP for appropriation, R&D requires either a proper IPP regime or a public support. Finally, it legitimates the idea that in the absence of a proper IPP regime, private innovators may resort to substitution solutions such as GURTs genes.

[36] Using data from two innovation fairs from the 19th century, one hosted in 1851 in the UK and one hosted in 1876 in the US, she showed that some sectors - those that offer alternative protection to patents such as trade secret - disproportionately attracted innovation in patentless countries. Her analysis was strengthened by a "natural experiment": the Netherlands abolished patent protection in 1869. Significantly more innovation was discovered in the Netherlands in sectors where secrecy could efficiently replace patents after the end of patent laws.

The choice of a 19th century fairs allowed to mitigate endogeneity issues (according to Moser, lobbying of innovators for more protection was weaker then than in the 20th century) and selection bias. Indeed, contrary to patents data, fair present both patented and unpatented innovations - though unpatented innovations are likely to be underrepresented to avoid copy. Despite the author's precautions, it is quite likely that some selection bias remained across inventors' nationalities. Indeed, transportation costs for British inventors to join the UK fair must have been lower than for innovators from Wurtenberg. Countries distant from the fair host probably overrepresented innovations from most profitable sectors.

Chapter 4

Economic assessment of R&D on varieties

Introduction

We saw in the previous chapters that research and development led on crops varieties has transformed deeply the agricultural production over the 19th and 20th centuries. Public policies have been at the core of the development of R&D programmes over varieties. The role of policies has materialized, first, by direct operation of research by public agencies. They have also been essential in the orientation of privately led research, through the design and implementation of intellectual property rights, and public subsidies to the private sector. The strong implication of public policies in agricultural innovation, and the burden this represents for public budgets, make it legitimate to evaluate their outcomes, as well as their costs. First, evaluations should be led in order to question the policies that have been implemented. The justification of public expenses, or of an institutional framework that seems to advantage some actors over others (patents are often criticized for granting a monopoly to large firms), would be more convincing if it could be based on a proper costs-benefits analysis. Second, evaluations should also provide useful information to set the direction of future policies. Indeed, unbalanced cost-benefit analysis of R&D investments in favor of agricultural research would advocate for more private and public effort in this sector. Moreover, larger rates of return than in the rest of the economy highlight potential issues, questioning why the private sector does not invests on research on varieties until rates of return become comparable to the ones in other sectors.

We first present the theoretical framework that has been developed by the economic literature to estimate the values and costs of R&D on varieties. Then, we briefly review the empirical literature, in order to highlight some general features of the valuation of agricultural R&D. We finally underline the paradoxes that arise from the evaluations provided by the literature, and try to suggest some explanations.

1 Theoretical frameworks of analysis of the social value of R&D on varieties

Estimating the value of agricultural research requires, first, to define it. Most literature has been based on the definition and estimation of different surpluses, or welfares (Alston et al., 1995). They have compared the actual observation with a reference scenario, the counterfactual, that would have occurred, had the innovation not been discovered. The framework of analysis used to perform empirical estimations of the returns of agricultural research has evolved with the practices of R&D on varieties, although most studies are based on an original idea by Griliches (1958). The following section presents this framework and its evolutions.

1.1 Valuing competitively supplied innovation - Griliches (1958)

Griliches (1958) has first developed the theoretical analysis framework to estimate the returns of investment in research on agricultural varieties that has been implemented since then in most studies of agricultural innovation value. Griliches developed it to study the social value of hybrid corn. He aimed at comparing the total research expenditures with the social welfare gain due to improved varieties, in an economy where the agricultural output is produced on a perfectly competitive market (*i.e.* the agricultural output is produced at marginal cost). The estimation of research cost is rather straightforward (publicly available data, surveys, etc. -

in his study, Griliches relied on surveys), and the modeling discussions (about discount factor, essentially) are easily solved. The definition and estimation of social welfare, however, deserves further attention. Griliches developed a partial equilibrium framework to estimate the social welfare increase. Assuming consumers are indifferent between traditional and improved varieties (which was a fairly reasonable assumption for hybrids, but should be discussed for genetically engineered crops), the introduction of an improved variety does not shift the demand curve. The net change in social surplus is thus obtained from a shift in the supply curve.

Because Griliches aimed at showing that rates of return of R&D on agricultural varieties is larger than in the rest, when choosing between modeling options, he systematically adopted the assumptions and strategies that underestimated the benefits of R&D outcomes and overestimated their costs. In his model, he used a constant price-elasticity demand curve, which had been shown to be a reasonable assumption by previous literature. Based on this literature, he assumed the associated elasticity, ε to be 0.5. He also acknowledged that the actual shape of supply curves when farmers cultivate the original and the new variety was much less documented, and thus difficult to model. To tackle this issue, he considered the extreme cases of perfectly elastic and perfectly inelastic supply curves. He assumed that the introduction of hybrids shifts both curves by the same factor (price or quantity increase by $k\%$ in the perfectly elastic and inelastic cases, respectively), which is the relative increase in production allowed by the innovation. This shift is exemplified by figure 4.1, but does not represent the actual shift of the supply curve. Indeed, it would be the case only if the cost of orignal and new seeds was identical.[1]. However, assuming the seeds are priced at their marginal cost, the net increase in social surplus is the area of the red surface minus the additional cost of production caused by hybrid crops adoption, *i.e.* the increase in seeds price.

Doing this only would overestimate the variation in social surplus. Indeed, the adoption of hybrid crops increases productivity (which shifts the supply curve downwards/rightwards). However, there is no reason that the direct costs borne by the farmers to plant the crops remain constant. Even if the market of seeds is perfectly competitive, it is then likely that seeds costs, at least, will increase (which shifts the supply curve upwards/leftwards), because breeding hybrids is more costly than

[1]The actual shift in supply curve actually depends on both the increased productivity of the new seeds and the price of these seeds. For instance, if the production cost of the new seeds completely offsets the gain in productivity they allow, there is no gain in social surplus.

breeding traditional varieties. Of course, the same discussion holds if a technology is discovered that both increases yields and reduces seeds production costs. Because the consequences of change in seeds costs would be different under the perfectly elastic and inelastic hypotheses, Griliches computed the variation in social surplus taking only into account the increase in productivity, dismissing temporarily the discussion on seeds costs (which provides a "gross" variation of social welfare). He calculated aside the additional costs in seeds production induced by the hybrid technology. He then subtracted the extra costs from the gross variation of social welfare, to obtain a "net" variation of total surplus.

If k is sufficiently small, then the demand curve can be approximated locally by a linear demand of slope ε. Then, the gross variation in social welfare are L_e and L_i in the perfectly elastic and inelastic supply cases are, respectively:

$$L_e = kp_n y_n \left(1 - \frac{1}{2}k\varepsilon\right) \qquad L_i = kp_n y_n \left(1 + \frac{1}{2}k\varepsilon\right)$$

Then $L_i > L_e$, and Griliches suggested to estimate the gross increase in social welfare using the expression of L_e, in order to under-estimate the benefit of R&D. This was the most conservative option, but it did not changes considerably the results, because the relative difference between these evaluation is rather low (around 7% with the values he adopted).[2]

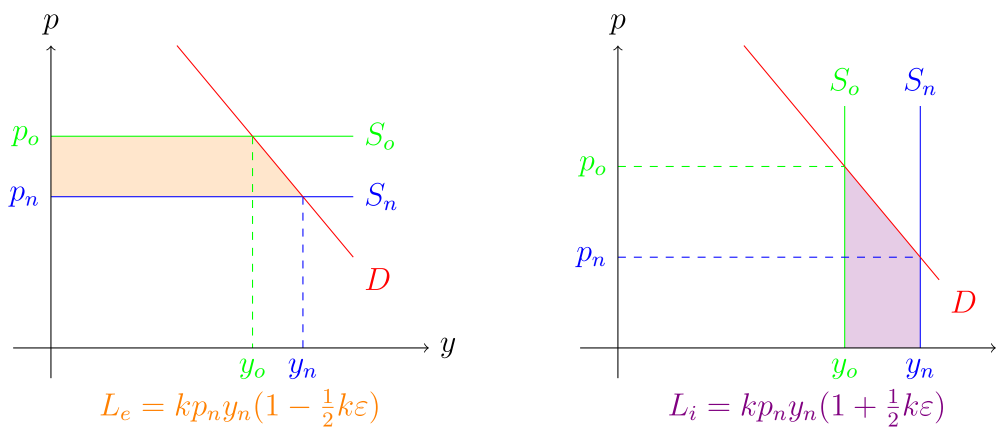


Figure 4.1: Agricultural R&D returns - perfectly elastic (left) and perfectly inelastic (right) supply

This way of estimating the variation of social welfare brought by the adoption of

[2] L_i and L_e, $(L_i - L_e)/L_e = k\varepsilon/(1 - k\varepsilon/2)$

a new technology, has been exploited in several studies following Griliches's work, as summarized in Alston et al. (1995). However, a key assumption in such estimation is that the additional cost of improved seeds for farmers, compared with pre-innovation, open-pollinated varieties, fully and only represent the additional production costs of these varieties. In other words, both hybrids and open-pollinated varieties seeds must be sold at their marginal cost, and the seed producer does not realize any commercial margin. If it is not the case, estimating social welfare change this way does not take into account the capacity of a seed producer to capture some rent from the innovation thanks to market power.[3] Hence, the method introduced by Griliches can be deployed only when the markets for crops are perfect, or when they are provided to farmers by a benevolent social planner. Yet, the development of intellectual property protection rights has provided innovators with monopoly rights over their inventions. Such evolution of the legal framework has strongly spurred the involvement of the private sector in the varieties research sector, thus advocating for the development of an adapted analytical framework.

Of course, as highlighted by Evenson (2001), research and development outcome *stricto sensu* does not explain all of agricultural productivity gains. Agricultural innovation also requires technology diffusion and *extension* to fully convert its potential into yields growth. When an innovation is discovered, it takes time and resources to make it available to all farmers. Evenson defines the "extension gap" as the difference between the observed average yield of a crop in the relevant region, and its best practice yields (*i.e.* the maximum yields that can be reached by planting the best available crop in optimal conditions, using all the available knowledge and technique). Hence, extension covers any information, infrastructure, material, or market completion that can be brought to farming in order to increase average yields closer to best practice yields. Improvement of agricultural education to farmers, diffusion of more complete information about the optimal growing practices, creation of irrigation infrastructures or supply of machinery for chemicals applica-

[3]To get an intuition of this, take the extreme case of an enhanced variety with higher productivity but the same production cost as the original one's. Suppose that the pre-innovation variety is sold at marginal cost. Assume, as well, that the innovator has sufficient market power to set its prices so that all farmers adopt the new technology, *i.e.* at the price that ensures that with one dollar of the new variety seeds, the farmers produce infinitesimally more output than they did with one dollar of the pre-innovation seeds. The supply curve would not shift at all. Estimating the benefits of research using the method illustrated by figure **??** would lead to conclude that research has driven no social benefit. However, a social benefit has been actually generated, though captured by the innovator.

tion or more reliable input supplies are examples of extension processes that have been crucial in increasing US yields during the last centuries.

1.2 Valuing oligopolistically supplied innovation - Moschini and Lapan (1997)

Moschini and Lapan (1997) suggested an evolution of Griliches-like models to evaluate the social value of enhanced agricultural inputs in general, and varieties in particular. As in the generation of models explained in the previous section, agricultural output is produced by farmers on perfectly competitive market. However, in this model, an original variety is initially provided to farmers by several suppliers, that may have some market power (the framework can treat both competitive and oligopolistic market structure). A research firm then discovers and supplies an enhanced variety. The innovation is immediately protected by IP rights for a given protection duration. The IPP prevents other suppliers from selling the new technology but is not broad enough to exclude the suppliers of the original one, and they can go on operating on the seeds market. To keep the analysis simple, no licensing option of any kind is considered. Any of the two technologies can be used by farmers to produce exactly the same output. Each technology has a proper production function, *i.e.* $y_i = f_i(x_i)$.[4] Hereafter, subscripts o and n stand for "original" and "new" varieties, respectively. Consider only the case of a *Hicks-neutral* innovation, *i.e.* $f_n(x_n) = f_o(\alpha x_n)$, $\alpha \geq 1$.

The qualitative results that are obtained under such assumption remain valid when considering other kinds of innovation (*e.g.* innovations biased towards one of the input factors). First, the original and new inputs are produced at constant marginal costs c_o and c_n respectively. For simplification, assume $c_o = c_n = c$. Seeds are offered for sale by seeds producers at respective prices ω_o and ω_n. Second, the agricultural output is sold by farmers on the commodity market. The demand of consumers for agricultural output on this market is an exogenous function $D(p^*)$, where p^* is the commodity equilibrium price p^*. The seeds and commodity market result in an endogenous demand by farmers for seeds. For any $i \in \{o, n\}$, the quantity of seeds exchanged, $x_i(p, \omega_i)$, is a function of inputs and commodity prices.

[4] It is assumed that the seeds are the only relevant input for simplification purpose. Assume any other input is integrated directly in the production function. Of course, it would be straightforward to make them explicit.

The equilibrium price on the commodity market thus depends on input prices, and we may denote the inverse demand function for seeds $\chi_i(\omega_i) = x_i(p^*(\omega_i), \omega_i)$, $i \in \{o, n\}$.

It is first useful to define the *efficiency price* of the new input, *i.e.* the cost, for the farmer, of $1/\alpha$ units of the new input, which produce the same output as one unit of the original input. The farmers will adopt the innovation if and only if its efficiency price is lower than the price of the original technology: $\omega_n \leq \alpha\omega_o$. Hence, the price set by the input supplier for the innovation is constrained. It is useful to note that the constraint is actually $\omega_n \leq \alpha c$ (because, whenever $\omega_o > c$, the suppliers of the original input will accept to lower their prices towards the perfectly competitive ones in order to retain market shares):

$$\omega_n = \min \left\{ \alpha c, \underset{\omega_1}{\operatorname{argmax}} \{(\alpha\omega_1 - c)\chi(\omega_1)\} \right\}$$

Assume the innovator never colludes with the suppliers of the original variety. There are thus three situations to be considered:

- The innovator would like to price its variety higher, but is constrained by the potential competition of the original technology to choose $\omega_n = \alpha c$. Following Arrow (1962), this is the definition of a *nondrastic* innovation: the innovator cannot price as a monopolist, otherwise its innovation is not adopted. This situation can be divided into two sub-cases:
  - The suppliers initially behaved competitively, *i.e.* $\omega_o = c$;
  - The suppliers had enough market power to behave oligopolistically, *i.e.* $\omega_o > c$;
- The threat of other providers is not biding, then $\omega_n = \operatorname{argmax}_{\omega_1} \{(\alpha\omega_1 - c)\chi(\omega_1)\}$. Following Arrow (1962), this is the definition of a *drastic* innovation: the innovator is able to price as a monopolist.

In any of these cases, the innovator prices so that it excludes all its competitors from the market. This is possible because the innovator is always able to price infinitesimally lower than its competitors, even when they price at their own marginal cost. If the innovation is non-drastic, the suppliers (of the original and new varieties) compete and decrease their prices until all the competitors are excluded, when the efficiency price of the innovation is equal to the marginal cost of production of the original technology. If the innovation is drastic, the new input is cheaper than the original one (in terms of efficiency price). These three configurations are summarized on figure 4.2, which represent their "translation" on the output market diagram.

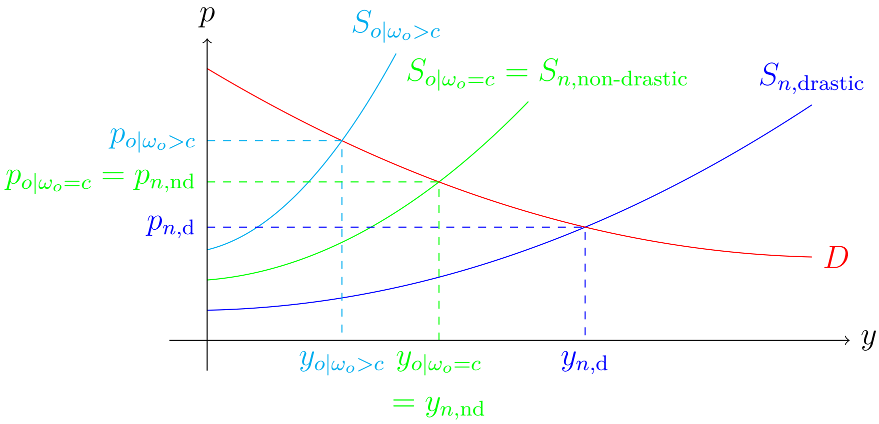


Figure 4.2: Drastic and non-drastic innovations on output market

Non-drastic innovation, competitive markets for old input. In that case, the introduction of the innovation does not bring any change to the output market, *i.e.* for the consumers and the farmers. Indeed, the efficiency price of the new variety is equal to the initial price of the original variety, so the supply function does not change (*i.e.* remains the green one on figure 4.2). The innovator captures all the social surplus variation, and hence the total change in social surplus between equilibrium before innovation and equilibrium after innovation, is $\Delta SW_{\omega_o=c,\text{ND}} = (\omega_n - c)\chi_n(\omega_n)$. Of course, in this configuration, the social surplus increases only if $\alpha > 1$. Otherwise, $\omega_n = c$ and the innovator has no possibility to get any profit from entering the market.

Non-drastic innovation, oligopolistic market of original variety. In that case, the total variation in social surplus has two origins:

- A change on the input market. The suppliers' profits are modified, as in the previous case. This change on the commodity market, denoted $\Delta\Pi^S$, comes from:

- The increase in the profit of the innovator, represented by the fist term in the RHS of (4.1).
- The loss of the rent that was captured by the suppliers of the original variety initially, as it was not priced to its constant marginal cost, represented by the second term in the RHS of (4.1).

$$\Delta\Pi^S = (\omega_n - c)x_n(p^*(\omega_n), \omega_n) - (\omega_o - c)x_o(p^*(\omega_o), \omega_o) \tag{4.1}$$

The non-drastic hypothesis implies $\omega_n = \alpha c$, thus:

$$\Delta\Pi^S = (\alpha c - c)\chi_n(\omega_n) - (\omega_o - c)\chi_o(\omega_o)$$

- A change on the output market. Because of the competition introduced by the innovator, the efficiency price of the new variety is lower than the price of the seed on the pre-innovation market. This changes the equilibrium on the agricultural commodity market. Hence, the Marshallian surplus, on this market, increases as the supply curve shifts from the cyan one to the green one on figure 4.2. We show in appendix that this variation in Marshallian surplus can be expressed as :

$$\Delta MS = \int_c^{\omega_o} \chi_o(\omega)\mathrm{d}\omega \tag{4.2}$$

The change in total surplus between the pre-innovation and the post-innovation situations is thus:

$$\Delta SW_{\omega_o > c, \text{non drastic}} = (\alpha c - c)\chi_n(\omega_n) - (\omega_o - c)\chi_o(\omega_o) + \int_c^{\omega_o} \chi_o(\omega)\mathrm{d}\omega$$

This expression of the variation in social welfare is actually valid in general in the non-drastic case, whatever the conditions on the market of the original variety (because in that case $\omega_o = c$). It is also straightforward to note that $\chi_n(\omega_n) = \chi_n(\alpha c) = \chi_o(c)/\alpha$.[5] This leads to $(\alpha c - c)\chi_n(\omega_n) = (c - c/\alpha)\chi_o(c)$. Hence, it is easy to display the variation of social surplus due to the innovation on figure 4.3 hereafter, which plots χ_o as a function of ω (the social surplus variation is the area delimited by the red line).

[5] Indeed, when the price of the new input is αc, the farmer is perfectly indifferent between buying the new and the original seed to produce a given quantity of commodity because 1 unit of the original input and $1/\alpha$ units of the new one produce the same quantity of output. Precisely because of this, the quantity of input that will be purchased by the farmer to produce its output will be $\chi_0(c)$ it it choses the original input, and $\chi_0(c)/\alpha$ if it chooses the enhanced input.

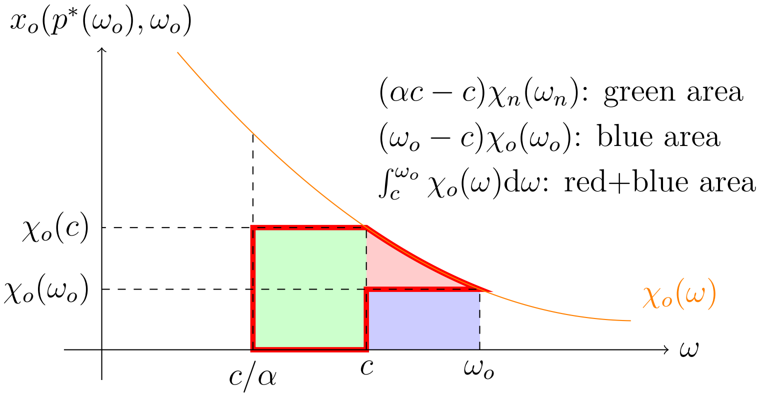


Figure 4.3: Social surplus increase yielded by non-drastic innovations on output market

Drastic innovation. The total social surplus change between pre- and post-innovation periods can be calculated using a method that is very similar to the one presented previously. In the non-drastic innovation case, the discussion about the competition on the market previous to introduction of the enhanced variety was not relevant (a competitive market was merely a special case with $\omega_0 = c$), and the same holds in the case of drastic innovation. The efficiency price of the new crop is lower than the marginal cost of production of the original variety, whatever the level of competition on the pre-innovation seeds market. Hence, the change in Marshallian surplus is obtained similarly:

$$\Delta MS = \int_{\omega_n/\alpha}^{\omega_o} \chi_o(\omega)\mathrm{d}\omega$$

And the change in input suppliers' profit is given by:

$$\Delta\Pi^S = (\omega_n - c)\chi_n(\omega_n) - (\omega_o - c)\chi_o(\omega_o)$$

Finally, thus, the total change in social surplus is:

$$\Delta SW_{\text{drastic}} = (\omega_n - c)\chi_n(\omega_n) - (\omega_o - c)\chi_o(\omega_o) + \int_{\omega_n/\alpha}^{\omega_o} \chi_o(\omega)\mathrm{d}\omega$$

When plotted on a figure similar to figure 4.3, the total change in social surplus has exactly the same shape.

Moschini and Lapan (1997) provided a new perspective on social benefit of innovation, that took into account the welfare effect of the market power conferred to the innovator by either institutional intellectual property protection instruments (PVPs, patents, etc.) or other ways of protecting innovation (secrecy, GURTs, etc.). It is quite likely, however, that some of the assumption implicitly or explicitly made by the authors may bias the measurement of the social value of an innovation in most cases. First, they assumed that the marginal production cost of the original and the enhanced variety are equal. When it is not the case, and, in particular, when the marginal cost of the improved variety is higher than the marginal cost of the original one, their model will overestimate social surplus driven by innovation. Second, they implicitly considered that the innovator keeps market power over innovation indefinitely, and did not take into account the increase in social surplus flow when the monopolist looses its position.[6] Indeed, when protection expires, the enhanced input becomes produced on a more competitive (or, at least, challengeable) market. Then, from that moment on, the supply curve will be shifted to the right on figure 4.2, increasing consumers' and/or farmers' surplus. This, on the contrary, would more probably underestimate the social value of innovation.

2 Quantitative valuation of R&D on varieties

Using the method presented in the previous framework, the economic literature has performed a large amount of empirical studies. It first estimated the valuation of publicly funded (or perfectly competitively supplied) innovation, and then integrated the constraints, highlighted by Moschini and Lapan (1997), into the evaluation of innovation when protected by IPP.

2.1 Empirical evaluations of publicly or competitively supplied funded innovation

Griliches (1958) estimated the flow of return of hybrid corn to society using the method presented in section 1.1 of this chapter, accounting for the hybrid corn

[6] However, Moschini and Lapan's framework applies to a flow of social welfare. In order to take the expiration of protection into account, it is possible to estimate welfare using their model while the innovation is protected, and then turn to the framework developed by Griliches (1958).

planted surface, for each year between 1933 (first year of significant cultivation of hybrid corn) to 1955. He also estimated total (both public and private) annual additional costs incurred by the development and production of hybrid corn, with respect to conventional varieties. He accounted for research expenditures since the first researches on inbred lines of corn in the beginning of the 19th century,[7] and additional production costs specific to the hybrid technology. He then computed the present value, in 1955, of total extra benefits and costs of hybrid corn, *i.e.* the discounted (at 5% and 10% rates of interest) sum of the variables described previously. In order to take into account the future costs and benefits of hybrids, he assumed that the annual flow of costs would remain constant (which, he stated, was a conservative assumption, because only adaptation to local conditions remained to be done by 1955, so most research costs to develop hybrids had been incurred long before). He assumed that annual flow of benefits would follow the same pattern (which, once again, is stated as a conservative assumption because, by 1955, diffusion of hybrids was only partial and thus social benefits were likely to increase with the broader diffusion of the hybridization technology). Using this method, he found a 700% cost-benefit ratio for the discovery and diffusion of hybrid corn in the US. Griliches finally remarked that public investment is necessary in research not only when social return is higher than private return (this is a *necessary* condition for public support, not a *sufficient* one: most innovation have had higher social returns than private ones), but, more precisely, when the difference between private returns and costs is too high to "induce the *right* amount of investment at the *right* time".

Alston et al. (1995) generalized and summarized more precisely the framework for empirical evaluation of agricultural innovation suggested by Griliches (1958). Numerous studies of publicly supported agricultural innovation have followed Griliches's path, adopting similar methods in order to measure the flow of social surplus driven by innovation. A deep review of such works has been provided by Evenson (2001, Section 4.1). The reviewed studies have been led in a wide range of countries locations (the reviewed studies covered countries from every continent), sizes and importance as agricultural commodity producers (*e.g.* studies on UK and Brazil were among the review), levels of development and agricultural research (*e.g.* the review included studies on both the US and Bangladesh) and have focused on var-

[7] Although research on inbred lines of corn had yielded, of course, useful outcomes long before the introduction of hybrid corn, such strategy ensures an overestimation of the research costs, and is thus likely to underestimate the cost-benefit ratios.

ious commodities (corn, soybeans, cassava, etc.). The most striking result of this review is that very high social internal rates of return (IRRs) of publicly funded agricultural R&D - much higher than usual IRRs - are broadly confirmed by empirical evaluations. Over more than 60 studies, only 5 found that IRR of such programmes is either not significant, or smaller than 20%. 3 others found that the lower bound of agricultural R&D is lower than 20%, but its upper bound is higher. Finally, 7 other studies, that focused on various commodity, found that the IRR of innovation is lower than 20% for less than half of the commodities they consider. Of course, the reviewed studies did not adopt the same strategies, and some of them treated technical issues (such as biasses) better than others. However, the fact that almost all of them tend to conclude to positive, significant and mostly high returns for agricultural on varieties research is a strong supportive argument in favor of its social desirability.

2.2 Empirical evaluation of monopolistically supplied innovation

A few studies have focused on the increases in social welfare brought by an innovation discovered by a private firm which obtains an intellectual property protection over it and, consequently, sells its outcome benefitting from the market power offered by IPP. As for the previously reviewed works, such type of studies depends on a simulated counterfactual, especially prices and yields evolutions, in order to compute surplus variations. In particular, the results drawn from these studies should be interpreted accounting for the hypothesis the counterfactual is based on (for instance, whether it supposes that the innovation is adopted in other parts of the world irrespective of the studied country's decision to adopt it).

Most welfare studies on the consequences of GM crops adoption focused on the US. Falck-Zepeda et al. (2000) provided an evaluation of the welfare increase, in 1997, driven by the introduction of the first transgenic cotton varieties cultivated in the United States. They built on the model developed by Moschini and Lapan (1997) to estimate the gains of different actors: farmers and consumers in the US, the owner of the IP rights over the innovation (Monsanto), the supplier of cotton seeds (Delta and Pine Land), farmers and consumers in the rest of the world. As did most of the studies based on the framework of Griliches (1958), they assumed a simple structure for the commodity market. Both demand and supply functions are linear, and the supply function is shifted downward by the innovation. Under such assumptions, they estimated that the cultivation of 1.8 million acres of *Bt* cotton in the US in 1997 was responsible for a 0.41 cents decrease of world prices of cotton. From this estimate, they deduce evaluations of surplus variations. Many of these results are rather intuitive: the US market benefited largely from the innovation, the innovator captured a significant share of total welfare increase, producers in the rest of the world suffered from the price cut triggered by innovation, while consumers in the rest of the world benefited from it. Meanwhile, other results might have been less predictable. First, the rest of the world, overall, is a net beneficial from the innovation: immiserizing growth, as introduced by Bhagwati (1958) and Bhagwati (1968), appears not to have occured. Second, perhaps more surprisingly, the farmers in the US capture, by far, most of the social benefits of the innovation (59% of estimated welfare gains accrued to farmers). One may have imagined that most of the welfare change had been captured by the innovator. However, as noted by the authors, the estimations have been led on data from the early years of the diffusion of *Bt* cotton in the US, which may explain the specificities of such results. The authors estimated the total world welfare gains driven by the development of *Bt* cotton to be around 240 millions US$.

Moschini et al. (2000) adopted a similar specification to focus on soybeans for the year 1997-1998. In the case where adoption of the improved variety is limited to the US, their results are similar to the ones of Falck-Zepeda et al. (2000) for cotton: consumers are always beneficiaries of the innovation around the world, farmers benefit from the innovation in the US and bear a cost anywhere else. However, contrary to Falck-Zepeda et al., they found, in that case, that the innovator is the one that captures most of the social welfare increase. They also took into account the possibility of adoption of the improved varieties of crops by farmers in other parts of the world than the US.[8] Such possibility "shares" more equally the welfare gains of farmers across the world: if an additional region adopts GM soybeans, the monopolistic power of the regions that had adopted it before decreases, the welfare of farmers increases in the additional region (and become positive), while the welfare of farmers in all other regions decreases (both the previous users of the innovation, because

[8]The authors name this possibility "international spillover", although the acception of this term here is different from its acception in the context of innovation economics, where "spillovers" refer to the positive externalities of one research firm on the other ones.

they loose some market power, and the non users, because they become even less competitive since the world price of the commodity decreases further). Of course, the sum of farmers' welfare over all the regions increases with the widespread use of technology. It also makes the commodity market more competitive, and hence increases consumers' surplus in all the regions. Finally, being able to make profit from exporting its technology, the innovator benefits from the diffusion of the innovation.

Price et al. (2003) compared estimates for the returns of three different crops: *Bt* and herbicide-tolerant (HT) cotton, and herbicide-tolerant soybeans. The direction of welfare changes is similar to the one found by previous studies (all actors benefit from the introduction of a new variety, except farmers in the rest of the world that have no or only partial access to the improved technology). However, the study showed some discrepancy across varieties. For *Bt* cotton, the innovator (Monsanto) and the US farmers share both 29% of returns, US consumers get 14% and the seed producer (Delta and Pineland) gets 6% of the benefits. The remaining 22% accrue to the rest of the world. For HT cotton, most surplus was estimated to be captured by consumers: US consumers get 57% of net surplus, while the innovator (Monsanto as well) and the US farmers only get 4.6% and 4.1% respectively, and the seed producer only 1.6%. For HT soybeans, finally, the results were different as well. Most welfare gain (40%) is captured by seed companies, while the innovator (28%) and the US farmers (20%) get comparable shares of surplus increase. The US consumers get a small share of the benefits (5%). The authors did not provide an extensive explanation for these differences, and it is difficult to get the intuition behind without more details on the model. Indeed, heterogenous elasticities may explain some of these results, but what one would expect considering them is far from the actual results: though demand elasticity is equal for GM cotton and GM soybeans, supply is much more elastic for cotton than for soybeans. This gives cotton producers a stronger negotiation power, which allows them to capture more profits, and reduces the welfare that can be captured by the consumers. One would thus expect the share of welfare accruing to farmers to be larger, and the share of welfare accruing to consumers to be smaller, for cotton than for soybeans. A lower share of welfare is observed for HT soybeans than for *Bt* cotton, but no higher consumers' surplus is observed simultaneously. Elasticity of supply of seeds and/or of innovation, which are not provided, may explain some of the results. The various actors may also lack information, while some may have stronger negotiation skills than other, which is not captured by the model.

Sobolevsky et al. (2005) provided a significant improvement in the evaluation of welfare effects triggered by GM crops introduction. Indeed, they accounted for the imperfect and weak substitutability of GM soybeans due to health and environmental concerns. They built a model in which standard, non-GM soybeans are initially produced in four different regions, US, Argentina, Brazil and the rest of the world (ROW) using a conventional technology. After the Roundup Ready (RR) technology is introduced, it can be adopted by farmers in any region. However, IPR is stronger in the US than in the other regions - and thus the price charged for RR seeds in the US are higher than anywhere else. The farmers may decide to adopt the RR variety or not, and the adoption rate is an endogenous variable of the model. For simplification reasons, the model assumed that only consumers in the ROW have differentiated demands for conventional and RR soybeans, and that they always prefer conventional to RR ones. The separation of GM and non-GM soybeans is assumed to incur a strictly positive *segregation* cost, that is born by the producers of conventional varieties, as long as the GM variety is produced in the concerned region. The model also accounted for US price support policies (*loan deficiency payments*) that effectively benefited to soybean producers (indifferently GM and non-GM ones) from 1998 to 2001.[9] The model was calibrated to match the 1997-1998 data, and the counterfactual supposed the innovation has not been discovered at all. First, the authors examined a series of scenarios, of different segregation costs both with and without US government farmers support programme (LDP). Lower segregation costs allow a better 3rd degree discrimination (Varian, 2009), and thus increase total welfare. Although the introduction of the innovation increases the profits of farmers worldwide, and contrary to the findings of previous studies, it may incur a net loss for US farmers if segregation costs are too high (because in that case, only the RR variety is produced and, because of stronger IPR in the US, a large share of the farmers' profits are captured by the innovator). Moreover, and important segregation costs increase both the absolute value and share of surplus increase captured by the innovator (because it makes consumers demand for more GM output). Consistently with previous studies, the innovator always captures a large share of total welfare gains. The main effect of US support policies is to redistribute the welfare, but their impact on distorsions (*i.e.* the welfare loss they cause) is almost negligible. As noted by the authors, such absence of significant

[9]The average loan rate, *ie* the average price that was guaranteed by the state, was around US$193 per megaton from 1996 on. The international prices got below this threshold between 1998 and 2001, triggering the mechanism.

welfare loss caused by public subsidies is due to the fact they substitute a distorsion to a market imperfection. Supporting the production of the commodity, they "artificially" increase the demand for seeds. Yet, the production of seeds is reduced, with respect to social optimum, by the market power of the innovator, so the subsidies act as a "second best" policy. Second, Sobolevsky et al. examine the consequences of a GM production and/or imports ban in different regions on welfare, in the case where no support programme is taken into account. They found that the ban of production or importation always reduces total welfare, although the magnitudes of the welfare losses are significantly heterogenous (from 11 to 1,489 millions US$).

A few works, however, have studied specifically the adoption of GM crops in other regions of the world. Pray et al. (2001) ran an analysis on the adoption of *Bt* cotton in China. While Falck-Zepeda et al. (2000) and Moschini et al. (2000) built their counterfactual on aggregated figures and simulations, Pray et al. (2001) relied essentially on local survey, adopting a randomized sample strategy. Their work is an interesting complement to those focused on the US and more or less free market, where demand elasticity is neither zero nor infinite. Indeed, in 1999 in China, cotton demand was perfectly elastic (the prices were set by the government, that bought any production level). Moreover, much of the planted seeds, even the GM ones, were either saved by farmers or counterfeit. Hence, the authors found that the share of welfare that is captured by innovators (in the Chinese case, research institutes and government agencies) is significantly lower, while the share of welfare captured by the farmers is larger, than what has been found by previous studies that focussed on the US. Gouse et al. (2004) studied the adoption of *Bt* cotton in South Africa and the distribution of its benefits. The particular case of South Africa is interesting because it is a rather small market, hence the adoption of any technology there is likely not to have any significant impact on world prices (contrary to adoption in the US, China, Argentina or Brazil). Then, neglecting transportation costs, South African consumers do not get any benefit from the introduction of GM crops in South Africa (the additional welfare then splits between farmers, innovators - Monsanto in this case - and seeds producers). The model also discriminated between small farmers who operate on drylands, large farmers who operate on drylands and large farmer who operate on irrigated land. Their results showed that, overall, South African farmers captured most of the benefits of *Bt* cotton. This is particularly true about the small-scale farmers (who capture 69% of total increase in welfare on their market), and large scale farmers who irrigate their cultivations (capturing

79% of total welfare on their market). Such finding tends to mitigate the idea that agricultural innovations mainly benefit to large, rich farmers. The counterfactual on which the paper is based seems to account for the adoption of the GM seeds in other parts of the world. Qaim and Traxler (2005) led a survey-based analysis of the adoption of Roundup Ready soybeans in Argentina. They found that these crops caused a net reduction in soybeans production costs, which is consistent with previous works. They also found that production costs reduction, and yield and gross margin increase tend to benefit more to small farms than to large farms, which is in line with the findings of Gouse et al. (2004). The scope of their study allowed to observe not only the welfare distribution for a given year, but its evolution on the 1996-2001 period as well. The counterfactual supposed that no innovation is adopted anywhere in the world. More significantly than in other studies, the Argentine farmers are the major beneficials of the innovation, as they were estimated to have captured more than 90% of the total welfare change in the country. Consumer's surplus gain has been negligible, around 1%, and innovator's profit has been only 8%. These two figures can be explained, respectively, by the fact that Argentina exports a lot of soybeans but consume few of it, and by the weak IPR system in Argentina. The model also computed the surplus variation in the US and in the rest of the world, and its results on these regions were consistent with those of previous works. The authors highlighted the negative consequences of a ban on imports in the ROW (especially in Europe) on exporting regions, that may have to reduce their total production of RR soybeans. Such ban would also be very costly for the banning region: the authors estimated that the net loss would be 941 millions US$ for the ROW only. However, such figure does not take into account, at all, the justification of such ban, namely the uncertainty over the potential environmental consequences of GM crops adoption. Accounting for it may well mitigate this conclusion.

The case of second generation of GM crops is quite specific and the evaluation of their social value will deserve further attention by future works. First generation GM varieties modify the mix of inputs to produce an output similar to conventional varieties' one. This reduces the production costs, and hence shifts offer curve upwards (or holds it constant in the limit case where innovating firms are able to capture all the extra surplus generated by the innovation). Public acceptance concerns reduce slightly consumers' willingness to pay for GM products compared to conventional ones,[10] shifting demand curve downwards, but this has been taken into

[10]Lusk et al. (2005) estimated that consumers' willingness to pay is 23% higher on average for

account when calculating surpluses (Sobolevsky et al., 2005). This phenomenon of a decreased willingness to pay for GM commodity is less obvious when the GM output is an intermediary production factor, such as soybean, or when it is not consumed as food, such as cotton (Pray et al., 2001). Second generation of crops, however, face a different reaction from the public. Indeed, they change the characteristics of the output (of course, this is also the case for some conventionally bred crops and the same evaluation issues arise for them). When such characteristics are easily observable (*e.g.* a better taste, as it was hoped to be the case for Flavr Savr tomatoes), demand curve shifts upward and, as long as the shift is known, additional surplus is easy to calculate. However, other characteristics of improved crops are not as easily observable by consumers as the taste of a fruit, and they may be more or less aware of the individual benefit they can withdraw from choosing these products (which can result from several causes, such as lack of information or time inconsistency). In this case, only "imperfect" (in the sense that it does not take fully take into account all the value of the crop's characteristics), if any, shift of the demand curve will arise and the computation of surplus proves much more difficult (Qaim, 2009). Then, modeling strategies to take them into account are more complex. For instance, whenever the crop is dedicated to improving health, the approach suggested by Stein et al. (2006) on golden rice applies, which defines the value of the innovation as the health cost of the deficiency the new crop aims to tackle.

3 (Why) is investment in agricultural research on varieties insufficient ?

It is rather difficult to define and compute a social internal rate of return for privately developed agricultural innovations. In particular, the total costs incurred for research are difficult to estimate, both because their scope is difficult to set, and because data on private firms is not openly available. However, the studies reviewed in the previous section have estimated that the social welfare gains, in the early years of adoption (*i.e.*, in particular, when the full potential of the innovation was not achieved), have come near to a billion dollar per year, often more than twice the private profits they have driven. Restricting to publicly funded innovation on

GM-free products. They also showed that output improving GM crops are more accepted by consumers than first-generation ones.

varieties only, the internal rates of return computed are much higher than usual rates in other sectors of the economy. If such findings were perfectly reliable, they would advocate for more investment in R&D on varieties, and, most probably, more public support for this activity.

Assuming the social IRR calculated by empirical studies are reliable, one may ask why no more research effort is undertaken by public agencies or governments. Information imperfection may explain some of this paradox: research and development, especially on agricultural varieties, is a long term activity, that implies to have a good forecast of the future state of markets. As mentioned previously, it may happen that the outcome of a research programme, that was aiming at meeting the consumers needs when it was launched, does not do so anymore when it succeeds (to some extent, it has been the case for the Flavr Savr tomato). Risk aversion may also be a complementary explanation. Although successful research projects, such as *Bt* or herbicide tolerant GM have driven huge benefits, some others, such as the Flavr Savr tomato, have failed - most often meaning the end (or the merger) of the firm that had launched it.

In addition, several reasons may cause the IRR of varieties innovation to be overestimated. First, as highlighted by Evenson (2001), some estimates may suffer from a selection bias. Indeed, many works, such as Griliches's one, estimate the benefit-cost ratio of a research process that has actually been successful. Yet, a significant share of research programmes either never succeed, or succeed "too late" (*e.g.* after a competitor has filed a patent over a similar innovation, or after the needs of consumers have evolved and they do not value it anymore). These programmes incur important costs, that should be taken into account in the evaluation of the research process, but are set aside when considering successful research only. However, even studies focussing on aggregate programmes (which, hence, account for both successful and unsuscessful researches) report high rates of return as well, which tends to prove that the selection bias may be disregarded as a significant "error term" in estimates values. More generally, the boundaries of the costs of an innovation may be difficult to set, because of the sequential nature of innovation. Second, the assumptions the counterfactual is built on play a critical role in the evaluation. For instance, comparing production costs per acre implicitly assumes a constant cultivated surface across observation or simulation and the counterfactual. The assumption that the cultivated surface would have been the same if the innovation had not been introduced (*i.e.* only the yield of production would have changed) has only been questioned recently (Hertel, 2012). Finally, a significant share of studies did not take into account the segregation costs that may follow the development of further varieties (Moschini, 2006). For example, banning the imports of GM crops in some European countries is not only costly because it prevents consumers that would prefer cheaper GM crops, it also incurs a significant cost of identity preservation. More generally, it has often been assumed (cf previous section) that the commodity produced using the new variety is perfectly equivalent (with respect to consumers' preferences) to the one produced using older varieties and product differentiation is frequently neglected.

The debate on the actual rate of return of agricultural R&D is stil quite vivid. Due to many sources of biases and uncertainty, it appears difficult to conduct a rigorous cost-benefit analysis. The large dispersion of estimates makes it difficult to draw clear policy recommendations out of them, although quite high values support the assertion that investment in this sector is insufficient. However, it seems that none of the reviewed studies valued the environmental impact of agricultural R&D on social welfare, which can strain its return, at least from a social planner's point of view.

4 Social value of agricultural innovation in presence of environmental externalities

As shown in the previous chapters and this one in particular, the existing literature allows to tackle various questions related to research and development, and in particular in the agricultural sector. However, it does not offer a sufficiently complete framework to analyse thoroughly the environmental impacts of agricultural R&D. Some questions related to environmental issues and R&D on varieties have been investigated already. It is the case for optimal research in the presence of pests adaptation (Goeschl and Swanson, 2003; Yerokhin and Moschini, 2008), or land use and greenhouse gas emissions (Hertel, 2012; Stevenson et al., 2011; Villoria et al., 2014). However, the integration of environmental issues in economic models of R&D on varieties is still limited. Few studies account for them, and those that do so generally consider only one environmental externality of innovation process at a time.

Various measurements of social welfare driven by agricultural innovation, and especially research on varieties, have been led in order to assess its outcome (Evenson, 2001). Such measurements have, generally, attributed large social benefits to innovation with respect to its costs, and thus advocated for a stronger commitment of public support to research and development in agriculture. The models used to assess the costs and benefits and innovation have evolved, from a framework dedicated to publicly led research that assumed no capture of rent by intermediary actors (Griliches, 1958) to a more comprehensive one, allowing to relax the assumption of optimally provided inputs (Moschini and Lapan, 1997). However, to our knowledge, no evaluation of any improved variety takes into account the environmental externalities of innovation outcome in welfare measures. This weakness of models and empirical studies analyzing social welfare driven by innovation on varieties has been highlighted by Moschini et al. (2000), as a potentially significant bias of their results. Pray et al. (2001) mention some of the environmental impact of the adoption of *Bt* cotton in China, respectively, but focus on the reduced pesticides use and cultures diversity only, and do not provide any quantitative evaluation of this effect. Qaim and Traxler (2005) qualitatively review the impacts of adoption of Roundup Ready soybeans in Argentina on the environment as well. They account for additional effects on chemicals use. They also include cultivation extension due to the increased profitability brought by the new technology, but, again, do not use them quantitatively in their welfare analysis. Although it would be much needed to account for every environmental effect, this would not come without significant issues along.

In chapter 1, we have reviewed the dimensions of the environment that are, either positively or negatively, acknowledged by the academic literature to be affected by the outcome of agricultural research and development. Among them, air quality is tampered by greenhouse gas emissions increased by some innovations and reduced by others. Soils quality depends on cultivation practices (tillage, in particular) or chemicals use and are thus impacted by any innovation that could change them. Off farm lands and water streams are impacted by chemicals runoff, gene flows. However, the environmental externalities of agriculture are still debated. Consequently, the pool of relevant aspects of the environment on which agricultural innovation should be studied is not stably defined yet. It thus deserves to be complemented by further studies.

4.1 Direction and magnitude of the environmental externalities of agricultural R&D

Once the relevant "variables" on which agricultural R&D has consequences are identified, determining the direction (positive or negative) and the magnitude of the impact is still a challenging issue. For instance, in section 3.3 of chapter 1, we mentioned, quoting Märländer and Bückmann (1999) and Demont et al. (2004), the case of GM varieties and herbicides. R&D outcomes on herbicide tolerant GM varieties may have increased the use of herbicides, but it has shifted the herbicides spread over cultivated land from a wide mix of various herbicides to a narrower and less toxic one, composed essentially of either glyphosate or glufosinate. However, studies supporting this conclusion of a positive impact of R&D through herbicides use are scarce, and hardly allow to quantify precisely such effect. A similar issue arises with the impact of R&D on biodiversity. The channels through which such effect occurs are not perfectly understood (land use is one of them, but it is neither the only one, nor is it thoroughly documented). Moreover, whether a given type of innovation will have positive impact on biodiversity hardly has a definite answer, at least for now.

4.2 Valuation of the environmental externalities of agricultural R&D

Finally, even if the direction and magnitude of the externalities of agricultural R&D on all the relevant aspects of the environment were correctly determined, translating it into welfare variation would require a social value for such externalities. The economic value of health is rather well defined, and evaluation methods have brought rather stable measurements (Dolan, 2000).[11] Hence, provided the impacts of agricultural R&D on health are determined, the social value (or cost) of this impact follows rather straightforwardly. The value of soil condition, as well, is rather straightforward to derive from the losses in agricultural productivity caused

[11] See Dolan (2000) for more precise details on the different methods of estimation of the social value of good health.

by soils depletion. However, other dimensions of environment on which agricultural R&D has an impact are much more difficult to valuate. The value of biodiversity, for instance, is quite discussed in the literature. Moran and Bann (2000) have acknowledged for components defining the value of biodiversity: direct use value (*i.e.* the value of goods and services directly produced by biodiversity and used either as production input or for consumption - *e.g.* any agricultural commodity), indirect use value (*i.e.* the value of goods and services produced by biodiversity that cannot be directly consumed or used as an input, but that improve production or consumption - *e.g.* pollination by bees), existence value (*i.e.* the intrinsic value of nature for merely existing - *e.g.* the value society give to knowing that polar bears are not extinct) and option value (*i.e.* the potential future value of biodiversity, yet unknown). Although the direct value biodiversity is rather straightforward to determine, indirect value is much discussed by the literature on ecosystem services (Jarvis et al., 2007), existence value is quite subjective and hence difficult to measure, and option value is uncertain by definition (Kassar and Lasserre, 2004).

Appendix

Moschini and Lapan (1997)

Non-drastic innovation, oligopolistic market of original variety. We explain here how to obtain the expression of change in Marshallian surplus (4.2). We first assume that indirect utility function of consumers V is quasilinear and depends on commodity prices p and consumer's income I, $V(p, I) = I + v(p)$. This allows to derive the consumers' demand $D(p) = -v'(p)$. We also define $\pi(p, \omega)$ the farmers' profits. On the agricultural commodity market, denote δMS a change in Marshallian surplus between the two equilibrium indexed by θ and ν. It is the sum of a change in consumer surplus and farmers profits:

$$\begin{aligned}\delta MS &= [V(p^*_\nu, I) - V(p^*_\theta, I)] + [\pi(p_\nu, \omega_\nu) - \pi(p_\theta, \omega_\theta)] \\ &= [v(p^*_\nu) - v(p^*_\theta)] + [\pi(p^*_\nu, \omega_\nu) - \pi(p^*_\theta, \omega_\theta)]\end{aligned}$$

Then, if the two states are sufficiently close, we approximate the RHS by its first order development:

$$\mathrm{d}M = v'(p)\mathrm{d}p + \left[\frac{\partial \pi}{\partial p}(p,\omega,r)\mathrm{d}p + \frac{\partial \pi}{\partial \omega}(p,\omega,r)\mathrm{d}\omega\right] \tag{4.3}$$

The demand is derived from the quasi linear utility as $v'(p) = -D(p)$. Moreover, by Hotelling's lemma (on output supply side), $S(p) = \frac{\partial \pi}{\partial p}(p,\omega,r)$. Finally, in equilibrium $D(p) = S(p)$. Hence, since $D(p) = v'(p)$, then $v'(p) + \frac{\partial \pi}{\partial p}(p,\omega,r) = 0$, and (4.3) becomes:

$$\mathrm{d}M = \frac{\partial \pi}{\partial \omega}(p,\omega,r)\mathrm{d}\omega$$

Using Hotelling's lemma once more on the input demand side, we get:

$$\frac{\partial \pi}{\partial \omega}(p,\omega,r) = -\chi_o(\omega)$$

Integrating the previous expression between the initial state ($\omega = \omega_o$) and the final state, we finally get the variation of Marshallian surplus:[12]

$$\Delta MS = \int_c^{\omega_o} \chi_o(\omega)\mathrm{d}\omega$$

Note that such expression does not allow to split up directly the increase of surplus due to the farmers and to the consumers. This would depend heavily on demand elasticity and would require a rather long discussion without adding very relevant information.

[12] The price ω in "after innovation state" must be expressed in "efficiency price", this is not the price per unit of input, but price per quantity of input that produce the same output as one unit of old input, so $\omega = \omega_n/\alpha = c$

Part III

R&D on varieties: a competitive process

Chapter 5

Models of patent races and theoretical analysis of IPP design

Introduction

The third and last part of this dissertation will study the process of innovation, in which research firms compete against each other to find the new variety first. This chapter will more particularly aim to understand how firms conduct their research activities, and how the structure of the research and development sector has an impact on such process.

In the economic literature on the process of research and development (R&D) and innovation, and on relevant public policy instruments, the work of Schumpeter (1942) is a founding milestone. Introducing the fundamental notion of "creative destruction", Schumpeter highlighted the social usefulness of granting an innovator with a monopoly over its invention, as an incentive for innovation - opposed to open competition that may not provide enough expected profits as incentive. Indeed, we saw previously that R&D is an example of market failure. In R&D, perfect competition conditions are not met, and thus market equilibrium is not socially optimal. Such failure legitimates public interventions and the use of relevant instruments to restore a social optimum. The oldest and most straightforward of such interventions is the grant of patent over a given innovation. Obtaining a patent ensures a firm a future flow of revenues, until the patent expires or until the innovation becomes obsolete. The expected profit is aimed at encouraging several firms to lead research programmes. Because a patent is granted to the first firm that has succeeded among those that have strived to find the innovation before the others, the R&D process across firms has often be named a *patent race*. In this chapter, we review the general models that aim to study the research process when several firms compete to discover an innovation.

Intellectual property protection temporarily replaces a market failure (the fact that innovation is a public good) by another one (the monopolist position of the patentee), and that is thus designed to balance the negative effects on welfare of each of them. The economic literature has tackled several questions that have emerged about this trade-off since Schumpeter. For instance, has patent duration an influence on the level of research that is undertaken in a given industrial sector and, if this is the case, is there an optimal patent length? Is stronger competition in the research sector socially preferable? Does it yields a better pace of research? How do firms behave during patent races? The answers to these question have highly important public policies implications, because innovation has been acknowledged as a major determinant of economic growth (Aghion and Howitt, 1992). In the current section, we present a model, inspired by the existing literature, that allows to suggest answers these questions.

Two major categories of patent race models have been developed in the late 1970s and early 1980s, and have been intensively used subsequently: deterministic models, first, and stochastic models, second. In deterministic models, following the model of Dasgupta and Stiglitz (1980), innovation is literally bought instantaneously by innovative firms. In order to discover a new process or good, a firm is required to spend a given amount of money. Once the firm has spent that amount, it can implement the process or commercialize the enhanced product. The main weakness of such models is that in real life innovation is not only a question of money, but may be sufficient to tackle some questions about patent races. Another richer type of patent race model is the stochastic ones. Among the stochastic models, two categories may be distinguished, those, following Loury (1979) or Lee and Wilde (1980), in which the research effort is decided once and for all at the beginning of the patent race, and those, following Reinganum (1981), in which the research effort can evolve with time. Because the deterministic models do not account for the stochastic nature of innovation, we only mention them. The stochastic static models have been intensively used by subsequent literature, and we will build on them in the following developments, so we present them in details in the first section of this chapter. The model of Reinganum is richer, but it implies heavier calculations as well. Hence, it has not been applied intensively to analyses of IP systems, and we will not detail it either.[1]

In chapter 3, we have presented some of the institutional and legal features of the intellectual property protection systems in major agricultural regions of the world. These features of an IP regime (protection duration, research exemption, etc.), that are set by laws and regulations, have very important consequences on the economics of innovation, and on the market of the new developed products. For example, reducing the duration of protection is likely to increase the discounted value of expected welfare once the innovation is discovered, but will reduce the incentive for innovation as well. A large share of literature has focused on the analysis of the different characteristics of IPP in general (not particularly agricultural one), and on how they influence the immediate next innovation, the subsequent ones, or the structure of the market. In the second section of this chapter, we review different aspects of IPP studied by the existing literature. Most of this literature builds on the model of Loury and Lee & Wilde presented in the first section. We first focus on the two most straightforward characteristics that define an IPR, namely the duration for which protection is granted, and the breadth of the protection. Then, we review the models that study how IP regimes have an influence on the possibility to "invent around" a protected innovation, and on subsequent discoveries and inventions. Finally, we review how slight modifications of IP regime strength (in particular, the possibility for those inventors that did not discover first the innovation to take part in the market) may allow to obtain a more efficient balance between incentive for innovation and welfare loss.

In the last section of this chapter, we review the models of innovation race that have been adapted to the specificities of research and development on agricultural varieties. Indeed, the innovation on plant varieties is quite particular, for several reasons. A first one, that we mentioned in chapter 1, is that the development of new crops has consequences on the environment. A second one is that all vegetal innovations are not protected by patents that exclude other research firms from

[1]For a detailed and well commented presentation of Reinganum's model, see Dockner et al. (2000).

using protected material for further innovation. A third one is that obsolescence of an innovation occurs in a different manner for plants. In the general case, an innovation gets obsolete because it is “taken over” by the state of technology: other technologies, discovered subsequently, meet better the needs of consumers (or reduce further production costs in the case of a process innovation), and older products or processes get less attractive. Such form of obsolescence may arise in the case of crops innovation. However, it is not the only cause of obsolescence, since pest adaptation is another one, that more specific to vegetal innovation (pharmaceutical innovation is the other major field that shares this feature).

1 Stochastic static model of innovation race

Deterministic models are well adapted to study a monopolistic structure of the innovation market. However, they come to the conclusion that at most one firm leads research when the market is competitive, which happens because only the firm that incurs the strongest effort can win the patent race (Dasgupta and Stiglitz, 1980). This conclusion, contradicted by the intensity of competition in many sectors of R&D, especially on plant varieties, shows that these models are less adapted to study the innovation process when various firms can compete for innovation. Loury (1979), Lee and Wilde (1980), and Reinganum (1981) have thus developed stochastic models. In these models, any firm, whatever its efficiency in doing research, and the efforts it devotes to this endeavor, has a chance to win the race. The models by Loury (1979) and Lee and Wilde (1980), on the one hand, are static ones, because the decision of the R&D effort is set once and for all by the firms at the beginning of the game, while the model by Reinganum (1981) is dynamic, because the decision of the R&D effort can be adjusted throughout the race for innovation by the research firms. Although Reinganum’s model is thus more refined than the one of Loury and Lee & Wilde, it implies heavy calculations, and has thus not been adapted by the literature to focus on specific issues of IP design, in particular protecting agricultural research. Hence, we chose to present only the model of Loury and Lee & Wilde here.

1.1 Loury (1979)

Loury (1979) developed a model in which the time of innovation is a random variable that follows a Poisson law. An exogenous number of firms $n \in \mathbb{N}$ compete to be the first to discover an innovation. The winner of the patent race is rewarded with a constant exogenous flow of profit π for a duration $T \in \mathbb{R}^+$, until the expiration of the patent. At the beginning of the race, each firm $i \in \{1, ..., n\}$ decides the sunk cost it will invest in R&D, x_i. The constant Poisson parameter of firm i's innovation process is $h(x_i)$. Then, denoting τ_i the stochastic moment firm i discovers the innovation, the density of the probability law followed by τ_i is defined by:

$$\Pr(\tau_i \leq t) = 1 - e^{-h(x_i)t} \tag{5.1}$$

The expected value of τ_i is $\mathbb{E}(\tau_i) = 1/h(x_i)$. Moreover, $h(x_i)$ is the instantaneous probability of discovering the innovation, knowing that it has not been discovered previously:

$$\Pr(t < \tau_i \leq t + dt | \tau_i > t) = h(x_i)dt \tag{5.2}$$

Assume no spillover from R&D activity across firms, which allows to consider that the discoveries of the innovation by the different firms are independent events. Denote $\tau_{-i} = \min_{i \neq j}\{\tau_j\}$, $\tau = \min_i\{\tau_i\}$, $H_{-i} = \sum_{j \neq i}$, $H = \sum_{j=1}^{n}$, and $W_i(t, dt)$ the event "firm i wins the innovation between time t and $t + dt$". Because of the assumtion that innovations across firms are independent events, the probability that firm i wins the patent race between two periods t and $t + dt$ is:

$$\Pr\left(W_i(t, dt)\right) = \Pr\left(\{t < \tau_i \leq t + dt\} \cap \{t + dt < \tau_{-i}\}\right) = h(x_i)e^{-Ht}dt + o(t)$$

At any instant, if firm i wins the patent race, it will earn the flow of profit π for the patent duration T. Hence, with r the discounting rate, the value of winning the patent race, discounted at the moment it is won, is $\int_0^T \pi e^{-r\theta} d\theta = (\pi/r)(1 - e^{-rT})$. Then, the expected profit of firm i at the beginning of the patent race, $V_i(x_i, H_{-i})$, is:

$$\begin{aligned} V_i(x_i, H_{-i}) &= \int_0^{+\infty} \left[\Pr\left(W_i(t, dt)\right) e^{-rt} \left(\int_0^T \pi e^{-r\theta} d\theta\right) - x_i\right] \\ &= \frac{h(x_i)\pi\left(1 - e^{-rT}\right)}{r(h(x_i) + H_{-i} + r)} - x_i \end{aligned}$$

Loury considered infinite patents only ($T = +\infty$), which yields:

$$V_i(x_i, H_{-i}) = \frac{h(x_i)\pi}{r(h(x_i) + H_{-i} + r)} - x_i \tag{5.3}$$

These results have been obtained by summing over every possible moment firm i can win the patent race. Another way of getting the same result that brings a complementary perspective, is the one implemented by Loury in his article. He looked at every moment whether firm i has won the patent race before. At any moment t, if firm i has won the patent race before, it is earning a flow of profit π. If it has not, it gets noting. Calculations are slightly heavier, so we consider infinite patents only. Denoting $W_i^b(t)$ the event "firm i has won the patent race before time t", we get:

$$\Pr(W_i^b(t)) = \Pr\left(\tau_i \leq \min(t, \tau_{-i})\right) = \frac{h(x_i)}{H}\left[1 - e^{-Ht}\right] \tag{5.4}$$

So, the expected profit of firm i is:

$$\begin{aligned} V_i(x_i, H_{-i}) &= \int_0^{+\infty} \Pr\left(W_i^b(t)\right) \pi e^{-rt} dt - x_i \\ &= \frac{h(x_i)\pi}{r(h(x_i) + H_{-i} + r)} - x_i \end{aligned}$$

Moreover, the expected innovation date across all firms is:

$$\begin{aligned} \mathbb{E}(\tau) &= \mathbb{E}[\min(\tau_k)|_{k\in\{1,..,n\}}] \\ &= \frac{1}{\sum_{k=1}^{n} h(x_k)} \end{aligned} \tag{5.5}$$

Looking for symmetrical Nash equilibrium, the maximization programme of firm i is:

$$\max_{x_i} V_i(x_i, H_{-i}) \tag{5.6}$$

Define $x_i^* = x_i^*(H_{-i}, r, \pi)$ as the best reply to other firms strategy $(x_j)_{j\neq i}$, the associated first and second order conditions are

$$\frac{h'(x_i^*)(H_{-i} + r)}{(h(x_i^*) + H_{-i} + r)^2} = \frac{r}{\pi} \tag{5.7}$$

and

$$\frac{\partial^2 V_i}{\partial x_i^2}(x_i^*, H_{-i}) < 0 \tag{5.8}$$

respectively. The expected payoff for firm i when it adopts the best reply strategy to H_{-i} is hence:

$$V(x_i^*, H_{-i}) = \frac{h(x_i^*)(h(x_i^*) + H_{-i} + r)}{h'(x_i^*)(H_{-i} + r)} - x_i^* \tag{5.9}$$

Define x^* as the symmetrical Nash equilibrium R&D effort and $V(x^*)$ as the expected payoff for any of the firms. Then, x^* verifies:

$$\frac{h'(x^*)[(n-1)h(x^*) + r]}{(nh(x^*) + r)^2} = \frac{r}{\pi} \tag{5.10}$$

To check that this interior solution is, indeed, the solution of the maximization programme, it is sufficient that it satisfies $\partial V_i/\partial x_i|_{x_k=0\forall k} > 0$:

$$\frac{\partial V_i}{\partial x_i}|_{x_k=0\forall k} = \frac{\pi h'(0)[(n-1)h(0) + r]}{r[nh(0) + r]^2} - 1 = \frac{\pi h'(0)}{r^2} - 1 \tag{5.11}$$

Hence, if h is concave, it must hold that $h'(0)$ is high enough to ensure the interior solution is the Nash equilibrium. To investigate the impact of competition on equilibrium R&D investment, it is useful to note that (5.10) defines x^* implicitly as, for any i:

$$x^* = x^*(H_{-i}, r, \pi) = x_i^*[(n-1)h(x^*), r, \pi] \tag{5.12}$$

Differentiating this expression with respect to n yields:

$$\begin{aligned}\frac{\partial x^*}{\partial n} &= \frac{\partial x_i^*}{\partial H_{-i}}\left[(n-1)h'(x)\frac{\partial x^*}{\partial n} + h(x^*)\right] \\ &= \frac{\frac{\partial x_i^*}{\partial H_{-i}}h(x^*)}{1 - \frac{\partial x_i^*}{\partial H_{-i}}(n-1)h'(x^*)}\end{aligned} \tag{5.13}$$

For equilibrium stability reasons, it is necessary that, for any i, $\partial \hat{x}_i/\partial H_{-i} \leq 0$.[2] Moreover, since $h' \geq 0$:

$$\frac{\partial x^*}{\partial n} < 0$$

[2]Indeed, if that was not the case, the equilibrium would be unstable: one infinitesimal increase in R&D investment of one firm would increase the hazard rate of all the other firms, H_{-i}. Another competitor would thus increase its own R&D investment level, then another one, etc. On the contrary, if $\partial \hat{x}_i/\partial H_{-i} \leq 0$, the equilibrium is stable: if one firm deviates from the equilibrium and increases its R&D investment level, the others will react by decreasing their own level, restoring the equilibrium. Thus, $\partial \hat{x}_i/\partial H_{-i} \leq 0$

Hence, increasing competition reduces the investment per firm (Proposition 1 in Loury's article). Indeed, if the industry is at equilibrium and, *ceteris paribus*, another firm enters the patent race, any given firm is less likely to win. Hence, the individual expected profit decreases, while the R&D costs remain unchanged.

However, an increase in competition may strengthen research in the economy as a whole. From (5.5) in equilibrium:

$$\mathbb{E}(\tau) = \frac{1}{nh(x^*)} \tag{5.14}$$

Hence:

$$\frac{\partial \mathbb{E}(\tau)}{\partial n} \quad = \quad -h(x^*) \frac{1 + \frac{\partial x_i^*}{\partial H_{-i}} h'(x^*)}{\left[1 - \frac{\partial x_i^*}{\partial H_{-i}}(n-1)h'(x^*)\right] \left[nh(x^*)\right]^2}$$

which is positive if and only if $-h'(x^*)\partial x_i^*/\partial H_{-i} > 1$. The LHS of this condition is actually the reduction in the effort of firm i if any other firm increases its effort by one unit.[3] An increase in the number of firms will thus reduce the expected industry-wide innovation date if and only if a marginal increase in R&D by any single firm causes a reduction of a lower amplitude in the R&D effort of each of its competitors (Proposition 2).

It is then interesting to relax the hypothesis of an exogenous number of firms competing, and to observe the equilibrium when firms can freely enter the patent race (in that case, firms enter as long as expected profits are strictly positive). First, consider the case where R&D has strictly diminishing returns, *i.e.* for all $x \in \mathbb{R}^+$, $h''(x) < 0$. From (5.9), in equilibrium, expected profit of firm i is:

$$V_i(x^*) = \frac{h(x^*)}{h'(x^*)} \frac{[r + nh(x^*)]}{[r + (n-1)h(x^*)]} - x^* \tag{5.15}$$

[3] Suppose every firm incurs the Nash equilibrium R&D effort, and some firm $j \in [\![1, n]\!]$ chooses to deviate from this equilibrium, increasing its investment by a small amount dx_j. Its own hazard rate increases by $dh_j = h'(x^*)dx_j$. From the point of view of the other firms (that have not reacted yet), the hazard rate of the rest of the industry increases by dh_j. In other words, for any firm $i \neq j$, $dH_{-i} = h'(x^*)dx_j$. Then, noting the hazard rate of the rest of the sector has changed, firm i will react to stick to its best reply, and will increase its investment by $(\partial x_i^*/\partial H_{-i})dH_{-i} = (\partial x_i^*/\partial H_{-i})h'(x^*)dx_j$. Hence, if one of its competitors deviates from the equilibrium and increases its R&D effort by one unit, firm i will reduce its own effort by $-h'(x^*)\partial x_i^*/\partial H_{-i}$.

Because h is assumed to be strictly concave, $h(x)/x > h'(x)$. Hence:

$$\frac{h(x)}{h'(x)}\frac{r+nh(x)}{r+(n-1)h(x)} > \frac{r+nh(x)}{r+(n-1)h(x)}x > x \tag{5.16}$$

And, hence, whatever n, $V_i(x^*) > 0$. Individual profits are thus strictly positive. Assuming no entry/exit barriers, there is always an incentive for firms to go on entering the market, so the number of firms in the race naturally tend to infinity. It could not hold, however, that individual profits tend to a strictly positive value as the number of firms tend to infinity. Indeed, in that case, total profits of the industry as a whole would be infinite, which is not possible. Then when returns to scale of R&D are diminishing, endogenous number of firms tends to infinity, and individual profits tend to zero (Proposition 3).

Now let us relax the hypothesis of strictly diminishing returns (h is convex up to a certain $\tilde{x}$, and concave then).

$$\begin{aligned}\frac{\partial V_i}{\partial n}(x^*) &= \frac{\partial V_i}{\partial H_{-i}}\frac{\partial H_{-i}}{\partial n}(x^*) + \frac{\partial V_i}{\partial x_i}(x^*)\frac{\partial x^*}{\partial n}(x^*) \\ &= \frac{\partial V_i}{\partial H_{-i}}(x^*)\left[h(x^*) + (n-1)h'(x^*)\frac{\partial x^*}{\partial n}\right]\end{aligned}$$

because, by definition of x^*, $\partial V_i/\partial x_i(x^*) = 0$ and $H_{-i} = (n-1)h(x^*)$. Substituting the expression of $\partial x^*/\partial n$ from (5.13), we get:

$$\frac{\partial V_i}{\partial n}(x^*) = \frac{\partial V_i}{\partial H_{-i}}h(x^*)\left[1 + \frac{(n-1)h'(x^*)\frac{\partial x_i^*}{\partial H_{-i}}}{1-(n-1)h'(x^*)\frac{\partial x_i^*}{\partial H_{-i}}}\right] \tag{5.17}$$

It is clear that *ceteris paribus*, when the competitors of firm i increase their R&D effort, firm i is less likely to win the patent race. Hence, its expected profit at the beginning of the race decreases, $\partial V_i/\partial H_{-i} \leq 0$ $\forall x_i \in \mathbb{R}$. So, because $h(x) \geq 0$ for all $x \in \mathbb{R}^+$ by hypothesis, $\partial V_i/\partial n(x^*)$ is positive if and only if:

$$\frac{(n-1)h'(x^*)\frac{\partial x_i^*}{\partial H_{-i}}}{(n-1)h'(x^*)\frac{\partial x_i^*}{\partial H_{-i}} - 1} \geq 1 \tag{5.18}$$

Yet, this inequality is never verified: because $\partial x_i^*/\partial H_{-i}$ is negative and $h'(x)$ is positive by hypothesis, the numerator of the quotient in the LHS of (5.18) is negative. Moreover, the quotient $x/(x-1)$ is always lower than 1 for all $x \leq 0$. So the quotient in the LHS of (5.18) is always lower than 1.

So it is possible to say that equilibrium profit is decreasing in the number of firm competing on the R&D market. But this is all: contrary to the case where hazard rate is a concave function of investment level, with no more specification, it is not possible to say anything about whether it is always positive or not. If it is always positive whatever finite n, the number of firms tend to infinity. If it is not, there is some n_0 for which, if n_0 firms are on the market, another firm thinking about entering expects negative profits, so n_0 is the long term equilibrium number of firms in the R&D race (Proposition 4).

Loury compared the private and the socially equilibria. To define the social welfare, he assumed that there is no other welfare than the one derived from the cash flow going to the innovator (there is no additional consumers). This is, denoting π_s the social instantaneous flow of surplus when the innovation is discovered and if S the social welfare, $\pi_s = \pi$ and $S = \sum_{i=1}^{n} V_i$. First, assume an exogenous number n of competing firms, and denote x^{**} the social optimal R&D investment of any of the firms. In that case $S = nV_i(x^{**}, H_{-i}(x^{**}))$. Because x^{**} maximizes the social surplus, the first order condition of the social planner is:

$$\begin{aligned} 0 &= \frac{\partial S}{\partial x}(x^{**}) \\ &= n\left[\frac{\partial V_i}{\partial x_i}(x^{**}) + \frac{\partial V_i}{\partial H_{-i}}\frac{\partial H_{-i}}{\partial x}(x^{**})\right] \\ &= n\left[\frac{\partial V_i}{\partial x_i}(x^{**}) + (n-1)\frac{\partial V_i}{\partial H_{-i}}h'(x^{**})\right] \end{aligned}$$

Since $\partial V_i/\partial H_{-i}$ is negative for all (x_i, H_{-i}), then, for this condition to hold, it is necessary that $\frac{\partial V_i}{\partial x}(x^{**}) \geq 0$. Moreover, by definition of x^*,$\partial V_i/\partial x(x^*) = 0$, so:

$$\frac{\partial V_i}{\partial x}(x^{**}) \geq \frac{\partial V_i}{\partial x}(x^*) = 0 \tag{5.19}$$

As, whatever x_i,

$$\frac{\partial^2 V_i}{\partial x_i^2}(x_i, H_{-i}) = \frac{\pi(H_i + r)\left[h''(x_i)(h(x_i) + H_{-i} + r) - 2\left[h'(x_i)\right]^2\right]}{r(h(x_i) + H_{-i} + r)^3} < 0 \tag{5.20}$$

Hence, $\partial V_i/\partial x_i$ is decreasing in x_i and so:

$$x^{**} \leq x^{*} \tag{5.21}$$

When the market structure (*i.e.* n) is set exogenously, firms thus overinvest in R&D from a social point of view (Proposition 5).

As noted by Henry (2010), the assumption that $\pi_s = \pi$ intuitively ensures competing firms will over-invest from a social point of view. Indeed, because π is the monopoly profit of the firm when it is granted the patent, if only one firm runs for the patent race, it will invest precisely the socially optimal R&D effort (since it will aim to maximize the total private profit, which is the social welfare as well). If another firm enters the race, the research conducted will necessarily be excessive from a social point of view.

Now consider free entry/exit on the market, and define $x^*(n)$ the privately optimal R&D effort and $x^{**}(n)$ the socially optimal R&D effort when n firms are competing. Assuming symmetrical equilibrium, social planner's programme is:

$$\begin{aligned}
\max_{x,n} S &= \max_{x_1,\dots x_n,n} \frac{\sum_{i=1}^{n} h(x_i)\pi}{r(r+\sum_{i=1}^{n} h(x_i))} - \sum_{i=1}^{n} x_i \\
&= \max_{x,n} \frac{nh(x)\pi}{r(r+nh(x))} - nx
\end{aligned}$$

Optimal firm investment x^{**} and number of firms n^{**} hence satisfies the two first order conditions:

$$\begin{aligned}
0 &= \frac{\partial S}{\partial x}(x^{**}, n^{**}) \\
&= \frac{V}{r}\frac{n^{**}h'(x^{**})[r+n^{**}h(x^{**})] - (n^{**})^2\, h(x^{**})h'(x^{**})}{[r+n^{**}h(x^{**})]^2} - n^{**}
\end{aligned} \tag{5.22}$$

$$\begin{aligned}
0 &= \frac{\partial S}{\partial n}(x^{**}, n^{**}) \\
&= \frac{V}{r}\frac{h(x^{**})[r+n^{**}h(x^{**})] - n^{**}h(x^{**})h(x^{**})}{[r+n^{**}h(x^{**})]^2} - x^{**}
\end{aligned}$$

Rearranging terms yields:

$$h'(x^{**}) = \frac{[r + n^{**}h(x^{**})]^2}{V} = \frac{h(x^{**})}{x^{**}} \tag{5.23}$$

So x^{**} satisfies $h'(x^{**}) = h(x^{**})/x^{**}$. Moreover, from (5.22), n^{**} is a finite number.

Now consider the case in which a finite number of firms, n^*, enter the patent race in market equilibrium. In that case, market equilibrium profits are zero (if it was not the case, free entry/exit would lead other firms to get into the market). Hence:

$$V_i(x^*) = \frac{h(x^*)}{h'(x^*)} \frac{[r + n^*h(x^*)]}{[r + (n^* - 1)h(x^*)]} - x^* = 0 \tag{5.24}$$

$$\frac{h(x^*)}{x^*} \frac{[r + n^*h(x^*)]}{[r + (n^* - 1)h(x^*)]} = h'(x^*) \tag{5.25}$$

Denote $x^*(n)$ the private optimal R&D effort when n firm compete in the patent race. Since $h \geq 0$, $r + nh/[r + (n-1)h] \geq 1$ whatever $n \geq 1$, so (5.25) implies:

$$h[x^*(n^*)]/x^*(n^*) \leq h'[x^*(n^*)] \tag{5.26}$$

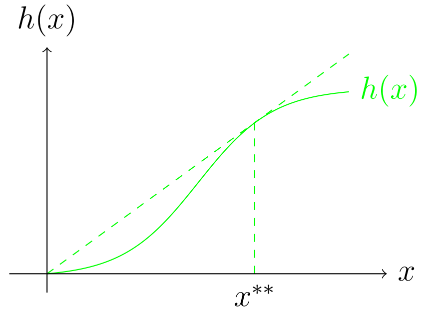
In the only case that allows n^* to be finite (*i.e.* when $h''(x) > 0$ below a certain threshold and $h''(x) < 0$ over that threshold), (5.26) implies that

$$x^*(n^*) \leq x^{**}(n^{**}) \tag{5.27}$$

This is easy to prove analytically, but the figure hereafter provides a graphical illustration of it. $h(x)/x$ is the slope of the line from the origin to the point $(x, h(x))$ and $h'(x)$ is the slope of the tangent to the curve of h in x. Hence the only possibility of verifying $h(x^{**})/x^{**} = x^{**}$ is where the tangent to the h curve has an intercept equal to 0. And it is then obvious that $h(x^*)/x^*(n^*) > h'(x^*)$ if and only if $x < x^{**}$.

From (5.21), for any given n, $x^{**} \leq x^*$. This inequality is true fo $n = n^{**}$ as well, which implies that:

$$x^{**}(n^{**}) \leq x^*(n^{**}) \tag{5.28}$$



Hence, from (5.27) and (5.28)

$$x^*(n^*) \leq x^*(n^{**}) \tag{5.29}$$

Since, from (1.1), $\partial x^*/\partial n < 0$, it comes that:

$$n^* \geq n^{**} \tag{5.30}$$

When free entry/exit leads to a finite number of firms entering the patent race, the number of firms in market equilibrium is thus higher than socially desirable. Of course, when free entry/exit leads to an infinite number of firms entering the race, too many firms enter from a social welfare point of view, because the socially optimal number of firms is always finite. Hence, competitive entry induces too many firms to join the race (Proposition 6).

Finally, Loury showed that it is possible to restore the social optimum combining a finite patent life and a lump-sum entry tax (Proposition 7).

Suppose, indeed, that an exogenous number of firms are running for the patent race, and that the patent has a limited duration T (once the patent has expired, competition drives the instantaneous rent to 0). Introducing a patent life T is equivalent to changing the income flow from π to $\pi(1 - e^{-rT})$. The profit expected by firm $i \in \{1; ...; n\}$ investing x_i in R&D is thus:

$$V_i^T(x_i) = \frac{h(x_i)\pi\left(1 - e^{-rT}\right)}{r(r + h(x_i) + H_{-i})} - x_i \tag{5.31}$$

Denote $x_T^*(n)$ the market equilibrium R&D investment of any firm when patent duration is sent to T. It is very easy to check that:

$$\frac{\partial x_T^*}{\partial T} \geq 0 \tag{5.32}$$

$$x_0^*(n) = 0 \tag{5.33}$$

$$\lim_{T \to +\infty} x_T^*(n) = x^*(n) \tag{5.34}$$

Since $x^*(n) \geq x^{**}(n)$, it is possible to choose $T = T^{**}$ so that:

$$x_{T^{**}}^*(n) = x^{**}(n) \tag{5.35}$$

For $n = n^{**}$ and $T = T^{**}$, it is likely that profits are not zero. Hence, supposing now n is endogenous, the economy would not be in equilibrium for $n = n^{**}$: if profits are strictly positive, firms will enter, if profits are strictly negative, firms will drop the race. It is thus necessary to impose a lump-sum tax (possibly negative) equal to profits in market equilibrium when the patent duration is equal to T^{**} and the number of firms is equal to n^{**}.

This model showed, first, that perfect competition in a patent race is not necessarily socially desirable. Second, it also explained that, although market equilibrium in presence of innovation is not necessarily socially optimal, it is possible, with very simple tools, to restore such a social optimum.

1.2 Lee and Wilde (1980)

Loury's model assumed that the R&D effort of any of the competing firms is a *stock*, decided and incurred once and for all at the beginning of the patent race. Lee and Wilde (1980) suggested another specification in which the competing firms decide, as in Loury's model, of their R&D effort at the beginning of the patent race, but that this effort is a *flow* incurred as long as the firm is doing research (it stops when the innovation is discovered). Loury's model thus depicted a polar situation in which research requires a large lump-sum effort at the beginning of the race, in which the recurrent costs of research are negligible, and Lee and Wilde's one depicted the opposite polar situation. The Poisson hazard rate of firm i is constant, and depends on the magnitude of effort decided at the beginning of the patent race,

x_i. The, the expected profit of firm i is slightly modified:

$$\begin{aligned} V_i(x_i, H_{-i}) &= \int_0^{+\infty} \Pr\left(W_i^b(t)\right)(\pi - x_i)e^{-rt}dt \\ &= \frac{h(x_i)(\pi - x_i)}{r(h(x_i) + H_{-i} + r)} \end{aligned}$$

The two models derive similar results regarding the industry at the aggregate level. The only differences arise when considering the R&D effort of individual firms: in Loury's "stock" model, individual R&D effort decreases when, either, another firm enters the race or when the competitors increase their own effort, while the opposite holds in Lee & Wilde's "flow" model (Reinganum, 1984). This difference is due to the fact that in the stock model, if either another firm enters the race or a competitor increases its effort, any other firm is less likely to win the race. The expected profit hence decreases, but without any decrease in the expected cost of research (because all the cost of research is spent once for all, whatever the duration of the patent race). In the flow model, on the contrary, such event would, everything equal, reduce the expected profit but would, as well, make the race shorter and so reduce the expected total cost of R&D.

2 Theoretical analysis of IPP design

2.1 The basic characteristics of IP: duration and breadth

IP duration

In his seminal work on optimal patent life, Nordhaus (1969, Chap. 5) explained that the socially optimal patent life lies at the equilibrium between two effects of increasing patent length. The positive effect of extending patent life is to encourage innovators to invest more in R&D. However, while the patent is enforced, the patentee is granted monopolist power over the market, which distorts social welfare. Increasing patent life increases the distortions. In his model, Nordhaus considered that innovation allows to reduce the production costs of an existing good. The R&D effort is endogenous: the stronger the innovator's effort, the higher the reduction in production costs.[4] For a given patent life, the innovator determines the private optimal R&D effort. Taking this behavior into account, the social planner can modulate the patent life to balance incentives for innovation and the deadweight loss associated with the monopolist market power.

However, in his model, Nordhaus assumed that a patentee can behave as a complete monopolist during the period of protection. This strong assumptions is verified only if the patent prevents competitors from "inventing around", *i.e.* discovering innovations that, while not infringing the patent, allow them to reduce marginal production costs as well. Hence, duration is not the only criteria defining the economic consequences of intellectual property protection. As highlighted by Nordhaus (1972), breadth is as important as length to define an IPP regime, and "life and breadth go hand in hand".

IP breadth

Discussing IP *breadth* (or *width*) faces a first challenge of definition. The main reason that makes IPP breadth more hazardous to define than IPP length is the difficulty to agree on a finite, objective and obvious set of criteria. [5] The relevant criteria of IP breadth may be the use that can be made of the innovation, the physical characteristics of a good (composition, design, etc.), its manufacturing process, etc. For example, in the United States, the "doctrine of equivalent" is broadly used in the definition of patent scope. This doctrine considers that a product that has the same use as another product protected by a patent is very likely to infringe such patent. This point of view sets rather extended boundaries for a patent, because two products may have the same use, while being very different in many aspects. Patents are thus broader in the US than in many other countries (Klemperer, 1990). The

[4]Initially, the good is produced at a constant marginal cost c_0, and commercialized competitively in quantity X_0; the innovation effort R cuts marginal cost of production by $B(R)$ (the innovator's marginal cost becomes $c_0 - B(R)$). After the patent expires, the improved technology becomes public, the product is sold at marginal cost $c_0 - B(R)$ in quantity X_1. While the patent is in force, the social surplus increases (as compared to the situation in absence of innovation) by the rent that is captured by the innovator from producing at cost $c_0 - B(R)$ and selling at market price c_0, this is $B(R)X_0$. After the patent of duration T expires, the technology is widely adopted and the good becomes competitively marketed at price $c_0 - B(R)$. Then, the rent captured by the innovator is replaced by the change in consumers' surplus as the increase in total surplus. Because demand is assumed to be linear, the change in consumers' welfare is $(B(R)X_0 + B(R)(X_1 - X_0))/2$.

[5]The definition of IP length may be marginally discussed, especially about the precise moment when protection begins, but such discussion has limited scope and consequences.

IP breadth can be used as an instrument to regulate competition among IP holders in the same class of products, or between an IP holder and other firms producing substitution goods. Broad IP protections limit the number of active patentees in a given sector, and impose that substitution goods available to consumers have very different characteristics from the already patented products. They ensure that more profits incur to the patentee, but also drive larger dead weight losses, because the IP holder will take advantage of the IP breadth to set high prices, and because the variety of products available to consumers is restricted. On the contrary, narrow protections of IP allow more firms to claim protection over inventions close to the already protected one. This offers a wider selection of substitutes, and thus increases consumers welfare, while reducing the patentee's incentive to innovate. As does IP length, optimal IP breadth is a balance between social surplus and incentives to innovate.

The literature on IP breadth is not as extensive as the literature focusing on patent length. Gilbert and Shapiro (1990) developed a model to study the optimal breadth of a patent system, and found that, under rather weak assumptions, the optimum is met for infinitely long, narrow patents (*i.e.* just as broad as required to ensure the expected profit of the innovator under infinitely lived patents is sufficient to encourage innovation). This is easy to understand when comparing the deadweight loss that results from extending patent duration, and the deadweight loss that results from widening protection. As the authors explain, "increasing the breadth of the patent typically is increasingly costly, in terms of deadweight loss, as the patentee's market power grows", while increasing patent length cause "a constant tradeoff between the additional reward to the patentee and the increment to deadweight loss".

Klemperer (1990) also analyzed the optimal mix of patent breadth and length in a more detailed model, obtaining slightly different results. As Gilbert and Shapiro, he assumed that a given expected profit must accrue to the innovator. He defined the patent breadth as the minimum distance between a patented product (the "genuine good") and other unpatented, substitutive goods in a spatial product differentiation model. Consumers are concentrated at a given place, and can choose between buying the patented product with no additional costs, or the same product at marginal cost (assumed to be 0) though having to bear transport costs (that are not *a priori* identical among consumers) per unit of good t. Each consumer may buy one unit of good (either genuine or substitute) is defined by a transportation cost and a reservation price for the good. The patent breadth (represented by a parameter $\alpha \geq 0$) is the minimum distance at which the competitors can be located, so the consumers decide to pay either the patentee's price p, or the transport costs to the substitution good αt.

The transportation costs represent the imperfect substitutability of the unpatented goods, or, alternatively put, the acceptability of the substitution goods. Moreover, to acknowledge that α is a measure of patent breadth, it is useful to interpret this spatial setting as follows. The consumers can either consume the patented product or the alternative one that is sold in the same place but is of lower quality. t is then the loss of marginal utility per unit of quality lost between the patented good and the alternative one for each consumer. It also represents the individual marginal (with respect to product quality) preference for the patentee's product over substitutes. α is the minimum loss in quality not to infringe the patent (when $\alpha = 0$, alternative good can be of the same quality as the patented one, when $\alpha \to +\infty$, the alternative good must be of much lower quality, which makes it by no means substitutable to the patented product). Each consumer decides whether it buys one unit of the good (it does so only if the good price is lower than its reservation price), which defines a total aggregated demand function. Hence a given consumer is characterized by two elements, its transport cost and its reservation price, and both are stochastically distributed over $[0, +\infty]$. Total deadweight losses have then two components: the deadweight loss caused by the patentee's market power (the consumers whose transportation costs are so high that they would not buy the substitute whatever, but who find the monopolist's price too high for them to buy the genuine good), and the transport costs (*i.e.* the disutility from consuming a lower quality good, named "switching costs").

The definition of patent breadth by Klemperer (1990) is somehow more specific than the one by Gilbert and Shapiro (1990). This explains the difference in the results. Gilbert and Shapiro adopted a rather general point of view, from which increased patent breadth increases the monopolist's flow of profit, whatever the way. This approach does not take substitution into account, and the origin of deadweight loss lies only in the fact that consumers buy less of the patented product, because the monopolist's price is higher than socially optimal. Klemperer, on the contrary, specifies that patent breadth represents the extent to which substitutes can "resemble" the genuine product. Hence, deadweight loss comes from both the consumption of lower amounts of the genuine good, and consumption of an imperfect substitute. He found that in the polar cases where all consumers have the same transport costs, it is socially optimal to implement infinitely narrow patents (Proposition 1). Because infinitely narrow patents, even if infinitely lived, would not drive sufficient expected profits to the innovator to innovate, under rather general assumptions, the socially optimal setting is to adopt the minimum width ensuring sufficient profit accrue to the innovator (Proposition 2). To understand the first point, it should be noted that if all consumers have the same preference for the genuine product, depending on the price set by the patentee, they will either all buy the genuine good, or all buy the lower quality substitute (if it is profitable for one consumer to adopt one of these behaviors, then it is profitable for all of them to adopt it). Hence, the patentee will always set a price at the highest level that avoids consumers buying the substitute, which depends on patent width. In that case, deadweight loss belongs only to the first category (consumers buy less than they would if the genuine good was sold at its marginal cost). To reduce this loss as much as possible, the solution is to set the lowest patent width that ensures sufficient instantaneous profit, *i.e.* the patent width that drives the requested expected profit when patent length is infinite. The second proposition provides the second-best solution that satisfies the condition of sufficient expected profit, since, in the case of uniform transport, total deadweight loss increases in patent width. In another polar case where all consumers have the same reservation price, infinitely wide patents should be adopted (Proposition 3). The intuition behind this result is that, in this case, it is very easy to cancel any deadweight loss, by simply ensuring the price of the genuine good is set at the common reservation price (all social surplus goes to the innovator, but there is no surplus loss). A consequence of these results is that if all consumers have equal transport costs and reservation prices, then any patent width is socially optimal (Proposition 5).

The models developed by Klemeperer, and Gilbert & Shapiro both allow to understand the implications of patent width regulation. It is interesting to note that although patent width is shown in these papers to be a full policy instrument, as important as patent length, it is not often used as such by policy makers, at least not directly. While IPP length is mostly set by law, the boundary of patent breadth is essentially defined by case law - the definition of precise boundaries of IPP breadth is often devoted to judges rather than to regulators. Of course, setting the patent duration once and for all, *in abstracto*, is much easier than defining *a priori* patent width, which, by nature, depends on a case-by-case analysis. However, this drives uncertainty about the extent to which a firm may commercialize a product without infringing a competitor's patent. It would be interesting to study how this uncertainty affects the innovators' behaviors. As highlighted by the authors of both articles themselves, their models do not account for innovation dynamics, since it considers a single innovation. However, most innovations are the result of a dynamic process, in which research is built on existing products and processes. Yet, in most regulations, patents do not include a research exception (*i.e.* conducting research on a product that is within a patent scope, even if this product is not commercialized, constitutes patent infringement), so the choice of patent width may preclude more or less further research on goods that are close to protected ones. Hence, static results concluding to the optimality of infinitely lived patents are likely to be questioned by dynamic approaches.

2.2 IP regime and subsequent innovations

IP and imitation

After discussing patent breadth, it is rather straightforward to follow on imitation of patented innovations. As shown by Levin et al. (1987), one consequence of patents is to make imitation costly for the patentee's competitors. They found that "patents raise imitation costs by 40 percentage points for both major and typical new drugs, by 30 points for major new chemical products, and by 25 points for typical chemical product". Gallini (1992) provided the first theoretical study in which imitation is assumed to incur a cost for its producer.[6] Knowing such cost, the imitators decide, endogenously, to imitate the genuine product or to remain away from the market.[7] In her model, a single firm was able to conduct research and, hence, to patent, and the competitors may only imitate the genuine product. The innovator decides either to patent the innovation or to keep it secret. She assumed a sequence of two consecutive endogenous decisions: first, the innovator decides to patent or to keep

[6]Imitation costs may have various origins (development of a substitute that is outside of the patent scope, payment of a licence fee, risk of being fined in case of illegal imitation, etc.), though, to be as general as possible, Gallini's model does not specify it.

[7]Contrary to previous studies in which either no imitation costs have to be born by imitators, and so all competitors imitate if they can, or imitation is assumed *a priori* not to occur.

its innovation secret, and then, the potential imitators decide whether they enter the market.

If the imitation costs are lower than a threshold V^{NP}, whatever the patent life, the innovator considers too many imitators will enter the market, and it proves more profitable to keep the innovation secret instead of patenting. If the patent life is shorter than a threshold T_I, whatever imitation costs, the innovator won't expect sufficient profit even if no imitator enters the market, and will, once again, prefer secrecy. If patent lasts longer than T_I, and if imitation cost are higher V_{NP}, then either the innovator patents and faces no imitation (if patent duration is sufficiently low for imitators not to expect a sufficient profit) or the innovator patents and imitators enter the market (if patent duration is sufficiently high for imitators to expect a sufficient profit). The calculations that prove these results are presented in appendix.

If the imitation costs are exogenously set, the socially optimal patent length is finite, and ensures no imitation occurs. Indeed, if imitation costs are lower than the threshold mentioned above, patent life has no impact on the market as the innovator keeps its invention secret. If imitation costs are high, the model becomes similar to the one developed by Nordhaus (1969) (because no credible threat of imitation exists), and optimal patent length is finite and does not depend on imitation costs. In between, optimal patent length is the one that ensures imitators are indifferent between entering the market and remaining out of it. More interestingly, when both imitation costs and patent length are set by the social planner, it is socially optimal to set sufficiently large imitation costs to preclude imitation and to set a finite patent life to ensure the innovator receives no more than the required expected profit to fund innovation. This contrasts sharply with the results of Gilbert and Shapiro (1990), and to Klemperer (1990) in the case of uniform transportation costs across consumers, in which optimal patent length was infinite. This difference in the results may be explained by two features of the model. First, in Gallini's model, both long patent lives and low imitation costs encourage secrecy. This point is not taken into account by previous models, and is obviously not socially desirable because it never leads to perfect competition on the market of the new good. The second point is that Gallini took into account the sunk cost of imitation that is paid by each imitator entering the market. In order to avoid the associated deadweight loss, it is desirable to discourage imitation, which is more likely to be achieved with wide patents.

Another important question regarding the optimality of IP design is the possibility, not acknowledged in most regimes, to invoke the *independent invention* (also know as *prior user rights*) as a defense against patent infringement (cf. chapter 3). In other words, if an invention is patented by a first firm, even if a second firm manages to develop the same innovation by its own R&D process and can prove it has not copied the first firm, the invention of the second firm will generally infringe the protection granted to the first one. Though this brings a strong incentive to be the first firm to invent, it is also quite likely to cause the loss of large amounts of R&D expenses whenever a firm discovers independently the same innovation as one of its competitors. Maurer and Scotchmer (2002) have focused on this issue and show that, as long as licensing is possible for the first innovator and under rather general conditions, the welfare loss resulting from useless, duplicated R&D effort may overcome the increased incentive for R&D. An "independent invention defense rule" (allowing the inventors that discovered a similar innovation independently to operate as an oligopoly) may thus be socially beneficial. Actually, in equilibrium, only one firm would actually patent the innovation, but the threat of competition from independent innovators would decrease its market power. Shapiro (2006) showed that the discussion introduced by Maurer and Scotchmer on duplication costs can be extended to reduction of social deadweight loss between monopoly and duopoly in general. Under his specification, it is necessary and sufficient to ensure the ratio of deadweight loss to profit under duopoly is lower than under monopoly for independent invention defense to be socially desirable.

IP and sequential innovation

The conclusions of the models presented so far are likely to change in a dynamic framework, when innovation is no longer a unique event, but rather a sequence of events. Since an innovation generally builds on previous ones, patent breadth and length do not only have an impact on present research, but on subsequent innovation as well. Green and Scotchmer (1995) developed a model in which one firm has the opportunity to discover a new product and, if it does so, a second firm can build on this first innovation to find, in turn, a second invention. Two strategies are available for firms. The first one is independence: each innovation can be commercialized independently from the other (although the market value of the first innovation may be 0). The second one is collusion: firms can agree to commercialize both products as a trust.[8]

For a given patent duration, the first innovator cannot capture all the available profit (*i.e.* the gross profit from jointly commercializing the two products minus the sum of R&D costs), even if an agreement is reached between the firms, either *ex ante* or *ex post* (Proposition 1). This means that the first innovator does not have all the bargaining power: the second innovator may always threaten it with possible competition after the second innovation is discovered. A consequence is that to encourage the first firm to innovate, patent life must be longer than it would be necessary to encourage both innovations independently (or if research on both inventions was conducted by the same firm). In the case both the cost and value of subsequent research are revealed after the first innovation is discovered, infinite patent breadth is socially optimal (Proposition 2). If only the cost of subsequent research is revealed after the first invention is discovered (and the value of its outcome is revealed later on), finite patent breadth may prove more desirable under certain conditions (Proposition 3). Finally, collusion between firms may increase social wel-

[8]If firms collude, the profit from selling the two products simultaneously is assumed to be higher than selling each product independently. Moreover, the authors assumed that the two products are imperfect substitutes, *i.e.* commercializing the first product alone drives higher profits than when the second product is sold on the market as well. It is possible that the second innovation infringes the patent over the first innovation (this is the case if the second innovation does not have a significantly higher quality than the first one).

The patent breadth is an exogenous threshold, defined as the minimum additional value the second innovation must have *per se* not to infringe the patent over the first innovation. The value of the second innovation is stochastic, and the second innovator has no influence on whether its innovation will infringe the patent or not. If the second innovation does infringe the patent over the first innovation, it can be commercialized only if the two firms reach a licensing agreement - then, they commercialize jointly the two products (hence, the independent and simultaneous commercialization of both products is only possible if the second product does not infringe the patent over the first one).

The sequence of innovation is as follows. At the beginning of the game, the value and cost of the first innovation is common knowledge, but only the distributions of second innovation cost and value are known. The first firm decides whether it innovates. If it does not, the game ends and no firm gets anything. If it does, it discovers the first innovation and patents it. Then, the second firm discovers the cost of the subsequent innovation. It decides whether it invests or not. If it does not, the second innovation is not discovered, and only the first product is marketed. If it does so, the second product, and its value, are discovered. To keep matters simple, it is assumed patents over both inventions begin at the same moment. If the value of the second innovation is high enough not to infringe the first patent, both innovations are commercialized competitively. If it is not, the second firm cannot commercialize its innovation without the agreement of the first innovator. However, collusion between firms is possible at two moments (subject to a legal framework that can prohibit it in any of these moments): either after the first innovation is discovered (*ex ante* agreement) or after the second innovation is discovered, only if it infringes the first patent (*ex post* agreement). If the second innovation does not infringe the patent, it is assumed the firms cannot collude even if it is profitable for them.

fare, especially in the case the first innovation has no autonomous commercial value (Proposition 5).

Sequential innovation may hence change the conclusions about patent breadth reached by the literature that assumed a single innovation. It can even question the conclusion that patents are desirable as ways of promoting innovation. Bessen and Maskin (2009) considered a situation in which two firms conduct complementary R&D (each firm benefits from its competitor's effort spillovers). When a patent system exists, only the firm that discovered the innovation can produce the good and commercialize it as a monopolist (which brings it an exogenous revenue) and, when a patent system does not exist, the two firms operate as a duopoly and each one get the same fraction of the monopolist's revenue.[9] If a single innovation is developed, then patents do actually stimulate research efforts. Indeed, private equilibrium level of R&D investment is higher than socially desirable if patents are implemented, and lower than socially desirable if they are not (Proposition 1). Hence, if patent are enforced, firms tend to overinvest in R&D, but this is often more desirable than the under-investment caused by lack of IP: under rather general conditions, social welfare attained is higher if a patent system exists than if not (Proposition 2). However, these conclusions are challenged in the case where subsequent innovations may be discovered. The authors assume that if a patent is granted, it is always broad enough to block subsequent innovation. Then, the behavior of firms is often less likely to differ from social optimum without than with patents (Proposition 6). The net social surplus can even be larger in equilibrium without IPP than in equilibrium with IPP (Proposition 7).

The results of models that adopt a dynamic perspective is rather different than those of static models such as Gilbert and Shapiro (1990) or, to some extent, Klemperer (1990). Wide and short patents are not necessarily socially desirable anymore, in order to encourage further innovation built on existing stock of knowledge. The model of Bessen and Masking highlighted, in particular, the positive externality of innovation: in absence of any agreements between firms, the first innovator does not take into account the option value it brings to the second innovation to further innovate. Even worse, if the subsequent innovation competes with the first one and the second innovator can freely develop over the first firm outcome, the loss in profit

[9] Hence, it is assumed that even without patents, the firms get a reward as a counterpart of innovation.

will reduce the incentive for the first firm to innovate. The question of sequential innovation is of particular relevance in the context of R&D on plant varieties. As will be explained *infra*, intellectual property protection over plant varieties has been designed - at least until the 1980s - conferring a large importance to the possibility of subsequent research and innovation.

Hopenhayn and Mitchell (2001) showed that, in addition to maximizing social surplus when a single innovation is to be discovered, the combination of patent breadth and duration may be sufficient to sort innovations that differ in their potential subsequent applications. Under reasonable conditions, the mix of patent breadth and length allow a patent office to sort innovations even without resorting to patent fees. Koo and Wright (2010) proved that the IPP length also has an influence on the timing of a subsequent innovation that built on a previously patented one. They examine the dynamics of two subsequent innovations, where the first one (which is necessary for the second innovation to be marketed) is discovered by a monopolistic firm that licensees to the second innovator. They consider then different situations under which research is led on the second innovation (monopolistic or competitive research environment, license negotiation before or after the second innovation is discovered, patentable or nonpatentable innovation).

2.3 Competition for R&D and IPP design

In the previous chapter, the discussion on patent races has given a first insight about the major role of competition in the R&D process. This section focuses on the influence of patent design on the intensity of such competition.

Sub-optimality of winner-takes-all IPP regimes

Most IPP regimes grant a right over the commercialization of the innovation to a single firm (in most cases, the first one to file the patent claim over the new product or process). Various authors have questioned the optimality of such characteristic. Moldovanu and Sela (2001) built a model in which at least three risk-neutral heterogenous[10] competitors decide of their effort in a race, in which two prizes are

[10]The competitors are heterogenous in the sense that the cost for making any effort level is competitor-specific.

granted, to the first and second ranked agents.[11] The objective of the social planner is not to maximize the effort of the winner (in which case the winner-takes-all scheme would be optimal) but the average effort across all competitors. This is particularly relevant when considering spillovers across research firms, and the impact of past experience in research on future R&D efficiency. If the common component of total cost is linear or concave, a winner-takes-all scheme maximizes average research effort. In the case it is strictly convex, average research effort can be maximized if a second prize is granted as well. The intuition behind such results is that with convex costs, it is socially desirable to ensure only the most efficient competitor provides the highest effort. However, whenever costs are concave, it can be more efficient to spread the effort among competitors. To do so, it is necessary to reward not only the winner, but also at least one of its followers. Szymanski and Valletti (2005) extended further the analysis of Maldovanu and Sela, assuming the cost of effort is random, and no longer private information. In such a stochastic framework where some actors are notoriously weaker than others,[12] awarding only one prize to the strongest one may reduce the incentives for this firm, and encourage it to make a limited effort. Indeed, aware of its relative strength, the strongest firm will expect that no competitor will make any effort, as they know they cannot ever win. The strong firm will thus rationally make only a marginal effort, knowing it would not be significantly challenged by firms what expect almost nothing from their R&D effort. However, if a second prize is awarded, it may prove interesting for a weaker agent to strive in the competition, which will, in turn, challenge the strongest firm and encourage it to make deeper efforts to keep its first rank.

The second prize plays a role that can be compared to exclusion as defined by Baye et al. (1993): it provides weaker competitors with incentive for effort despite

[11]The race is deterministic (the competitors are ranked according to their efforts). For firm $i \in [\![1, n]\!]$ where $n \in \mathbb{N}, n \geq 3$ is the number of competitors, total effort cost of effort x_i is

$$C(x_i) = c_i \gamma(x_i)$$

with $c_i \in [m, 1], m > 0$. Function γ is common knowledge, but the firm-specific parameter c_i is private knowledge (were it not, only the firm with the lowest marginal cost would take part in the race, because the other firms would know they have no chance to win the race). Only the distribution of the constant components of cost is common knowledge.

[12]The stochastic nature of the model is necessary for weaker firms to actually run for the race. In a deterministic model with perfect information, they would be aware of having no chance to win and would thus not run at all. The distribution of cost for the weaker firm is thus centered on higher cost values than the distribution of cost for the strongest one.

the fact they are aware of their weakness.[13] Baye et al. set a framework in which three firms compete. A firm can be either strong or weak, but at least two of them are identical. The social planner, who seeks to maximize the total effort undertaken by the firms, can decide how to share a given award between two of them. When the agents are identical, the social optimum is obtained by granting the first firm with all available award. In this case, the agents do not adopt strategic behavior, because none anticipates any of the other will rationally underinvest after realizing it has no chance to win. The case in which two agents are strong and one is weak is similar to the case in which two agents only compete (because the weak agent knows it is not very likely to win and thus will not make any effort). In such case, it is optimal to allow all award to the winner - the incentive to make an effort is all the stronger that the difference between first and second prize, because the second prize is the minimum reward a strong firm would expect even incurring a minimal effort. Finally, when one firm is strong and the other ones are significantly weaker, its is optimal to allow 25% of the total award to the second firm, and the remaining 75% to the first firm. In that case, the role of the second prize is to encourage weak firms not to refrain from investing effort in the race.

Denicolo and Franzoni (2010) considered the specific case of innovation races.[14] They found that the relevant parameter to discuss the optimality of the winner-takes-all system compared to a second prize are the ratio of the flow of deadweight loss over the flow of profits. Whenever the ratio under duopolist is large before the ratio under monopolist, a winner-takes-all system is preferable. One feature of the model deserves attention. The authors assume the firms set their effort before knowing whether a second prize will be granted, knowing only the probability α with which the social planner will indeed implement a second prize regime. Such specification thus imposes that the R&D effort of a given firm is the same under both regimes. One would think that whether second prizes are granted or not is a major feature of the overall IPP system of a country. Hence, it would be straightforward

[13] The exclusion principle suggests to exclude the highest bidder in an all-pay action - *i.e.* an auction in which the seller earns all the bids announced buy the buyers. In some cases, knowing that the bidder with the highest valuation of the good for sale is taken out can encourage higher bids from other buyers.

[14] They analyse the influence of second prizes in R&D efforts undertaken by two symmetrical firms. Innovation is assumed to follow a Poisson process, and the model is similar to Lee and Wilde (1980), with infinitely-lived patents. If a second prize is allowed, the first firm to discover the innovation operates as a monopolist until the other firm does so, and then both operate as a duopoly.

to compare two systems, allowing firms to bid a different R&D effort under each regime, which would be more realistic.

The case of agricultural varieties is particularly interesting to consider under the light shed by the previous discussion. First, maximizing average R&D effort across research fields is of particular relevance as social objective - which is adopted in Moldovanu and Sela (2001). Indeed, the capacity of a firm to conduct further research depends heavily on its relevant past experience in this sector, especially because it has allowed it to develop and enhance its own lines of plants. Hence, targeting only the maximized R&D effort from one firm is likely to keep this firm as the only innovator in subsequent research. On the contrary, ensuring that a well spread average effort is undertaken in the R&D sector is likely to encourage the diversity of inbred lines, and thus of further research. It would also be socially desirable to have a selection of lines available if any threat is discovered specifically on the most used varieties. Second, the values of second prizes depend on IPP regime in force. Under full patent regime, varieties are like any other innovation (at least when discussing the possibilities for other researcher to benefit from a second prize). Hence, if two firms A and B develop similar innovations and firm A patents it first, the "second prize" awarded to firm B is very limited. Indeed, it can neither commercialize the product nor build directly on this product for future development - the only "second prize" is then the experience accumulated in R&D. On the contrary, the research exemption regime (such as PVPs) grants a more valuable second prize to firm B, which is not only the experience in plant breeding but also the option to build subsequent innovations on the one claimed by firm A. Third, the framework of Szymanski and Valletti (2005), in which a strong firm with very deep relevant experience competes with much weaker and less likely to win (cf. chapter 1), is fairly frequent in R&D on varieties. Ensuring the weaker firms receive a second prize is then particularly justified.

Permissive IP

The previous section has discussed the possibility to grant a prize to firms in IPP race even when they do not rank first on the finish line. An interesting particular implementation of such possibility is the option of permissive IP, that rewards firms that discovered an innovation shortly after the first discoverer. In practice, when IPP regimes are available, they most often grant only the first firm who innovates with a monopoly right over the innovation for a given period.[15] As seen previously, no IP protection may also be justified by several reasons, as long as it does not prevent firms for innovating, and Plant (1934) already advocated for the abolition of patents, arguing that they over-reward the inventor.[16] Briefly, the rationale of patents is to accept the deadweight loss of a monopoly for a transitory period and the risk they induce for the competing innovators in the patent race as a counterpart for a strong incentive for R&D effort, and the disclosure of the innovation.

A first attempt of studying such mechanism has been undertaken by La Manna et al. (1989). However, their model is not much precisely specified, and Henry (2010) developed a more complete model of patent race to focus on the same issue. He aimed at studying more precisely the introduction of runner-up patents. Compared to La Manna et al. (1989), his model allowed him to show that runner-up patents are socially desirable under much more general conditions. As he explained, implementing runner-up patents may change two determinants of social welfare: they would have an *ex ante* impact on the research incentive (on the one hand, they reduce the grant for the first firm to innovate, and, on the other hand, they potentially offer some gains to the other firms) and an *ex post* effect on the social surplus (they threaten the monopolist position of the first innovator, and thus decrease the associated dead-weight loss). The question of the paper is to determine the conditions under which runner-up patents are beneficial from a social point of view, and to provide a decision rule to determine the optimal runner-up window duration. It provides a series of *sufficient* conditions so that it is the case.

The model considered a situation in which two firms run a single stage patent race, based on the specification of Loury (1979). One of the firms, denoted $i \in \{1, 2\}$, decides, at the beginning of the race, its R&D effort x_i, and innovation follows a Poisson process of hazard rate $h(x_i)$. Suppose firm i innovates first, at the moment τ_i. At that moment, this firm is granted a patent over the innovation, for a duration L. If its competitor, indexed by $j \in \{1, 2\}$ $i \neq j$, innovates, at time τ_j, during a

[15] IPRs for plants are actually not a special case in this debate, as they do not provide any right over the market of the protected innovation to firms that have not discovered first in the current patent race, as breeder's rights concern further races only.

[16] The absence of IP may not reduce significantly the incentive to innovate for several reasons: first-mover advantage granted to the first innovator allows it to keep its advance and may be a sufficient incentive *per se* for R&D effort, trade secrets may be a sufficient protection, the ability of competitors to copy the innovation takes enough time to be acquired so that the first innovator benefits from a strong market power for a sufficient period, etc.

"patenting window" of duration T ($\tau_i < \tau_j \leq \tau_i + T$), firm i gets gets a monopolist flow of private profit π_m between τ_i and τ_j, and then both firms get a duopolist private flow of profit π_d from τ_j, until the expiration of the patent (at time $\tau_i + L$). The competition among the two firms, when occurring, may be either *a la* Cournot or *a la* Bertrand. If firm j does not innovates during the patenting window (*i.e.* $\tau_j > \tau_i + T$), firm i gets a monopolist flow of profit from τ_i until the patent expires. S_m and S_d are the exogenous flows of social surplus when one firm operates as a monopolist and when the two firms operate a duopoly, respectively. Henry assumed the two firms identical, and, considering pure strategy, symmetrical Nash equilibrium only, defined x^* as the equilibrium investment effort.

The author showed (Proposition 1) that runner-up patents may decrease the incentives to innovate. Indeed, if $\pi_m \geq 2\pi_d$, then the runner-up patents decrease the equilibrium R&D effort, *i.e.* $dx^*/dT|_{T=0} < 0$. From now on, suppose this condition is met. Despite this disincentive effect of runner-up patents on innovation, they increase social welfare under rather general conditions (Proposition 2):

a. If the duopoly social surplus is high enough ($S_d > 2S_m$). In this case, the difference between duopoly and monopoly surplus is high enough for the increase in surplus with runner-up patents to offset the loss in R&D incentive.

b. If, under monopoly, social welfare is not too high compared with private profit ($S_m[r/(h(x^*) + r)] < \pi_m$);

c. If demand is linear and firms compete *a la* Cournot or *a la* Bertrand.

To finish with, Henry (2010) highlighted the fact that "we cannot yet rule out that runner-up patents appear socially beneficial only because the other existing tools [patent length and breadth] are not optimally set". Indeed, patent length was supposed given ($L = +\infty$), and patent breadth was supposed maximal (once the patenting window has expired, followers earn no profit at all). It is thus legitimate to ask whether runner-up patents are still relevant form a social welfare point of view when patent length and breadth are set optimally. Henry (2010) adopted a similar definition of patent breadth to the the one set by Denicolo (1996), where a parameter α captures the patent breadth. He defined π_F as the profit of a follower (*i.e.* any firm for which innovation occurs after the expiration of the patenting window), and S_0 the flow of social welfare under perfect competition. He found that a strictly positive patenting window is socially desirable if two conditions are met (Proposition 3):

$$\frac{S_d - S_m}{\pi_m + \pi_F - 2\pi_d} > \frac{S_0 - S_m}{\pi_m + \pi_F} \quad \text{and} \quad \frac{S_d - S_m}{\pi_m + \pi_F - 2\pi_d} > \frac{-S'_m(\alpha)}{\pi'_m(\alpha) - \pi'_F(\alpha)}$$

These conditions are interestingly intuitive. First, consider the first inequality. $S_d - S_m$ is the increase in social surplus when a patenting window is implemented, and $S_0 - S_m$ is the increase in social surplus when the patent system is removed. The sum $\pi_m + \pi_F - 2\pi_d$ could be interpreted as the decrease in innovation incentive when a runner-up patent is implemented. Indeed, $(\pi_m + \pi_F)/2$ is related to the R&D incentive when, because symmetrical firms have the same probability 0.5 to innovate, getting a flow of profit π_m, and to loose the race, getting a flow of profit π_L. In addition, π_d is related to the flow of profit firms may expect when they both file a patent. Moreover, the sum $\pi_m + \pi_L$ as the decrease in innovation incentive when the patent system is removed. Indeed, $(\pi_m + \pi_F)/2$ can be considered as the expected instantaneous profit for any firm under patent system, and without patent system, as firms produce the good until all profits dissipate, expected profit is 0. Hence, the left hand side (respectively the right hand side) of the first inequality is a measure of what runner-up patents (respectively patent length) add to social welfare. The second inequality makes a similar comparison, though between patenting window and patent breadth: $-S'(\alpha)$ measures the increase in social surplus when patent breadth is reduced, and $(\pi'_m(\alpha) - \pi'_F(\alpha))/2$ measures the variation of the R&D incentive when patent breadth decreases.

When firms are not identical, patent and patenting window length can be an instrument for public policy to sort them by efficiency in research. Imagine that firm a and b compete, and that firm a is more efficient than its competitor. Firms know which one is the most efficient, but the social planner does not. If, when the firm applies for the patent, the social planner proposes two sets of patent length and patenting windows (one with a shorter patent life and no patenting window, and the other one with a longer patent life but a non-zero patenting window), provided the sets are well calibrated, the more efficient firm will chose the longer patent life, and the less efficient one will chose the shorter patent life. Indeed, the most efficient firm knows it is more efficient, and hence if it innovates first it will consider its competitor will hardly innovate during the patenting window. On the contrary, the less efficient firm, on innovating, will consider quite probable that its competitor will innovate soon, and will chose to ensure it gets monopolist profits, even if for a shorter period.

The literature on permissive patents sheds an interesting light on agricultural IPP as well. Indeed, research exemption offered by plant variety protection features comparable advantages. First, as discussed in the previous section, it encourages more average R&D effort by providing an incentive for less efficient firms to conduct research, encouraged by the option value of further research. Second, it also reduces the deadweight loss caused by duplication of research. Indeed, firms competing for any IP protection in R&D on varieties may develop close varieties, of which one only will be patented. Under full patent, if these varieties are too close, the losers of the patent race will neither be allowed to commercialize the output of their research, nor to conduct further research based on these varieties. Useless duplication is then most probable. However, under PVP, such close varieties can be both further developed alone, or improved with the traits of the protected crop, giving birth to subsequent innovations. Hence, lines developed by firms that do not succeed in the patent race are not lost, but remain available for development later on, and this possibility is undoubtably more likely under plant variety protection scheme.

3 Modeling R&D on agricultural varieties and its specific features

In this section, we review the way the specificities of agricultural innovation have been treated by economic theory. First, we present a model designed to study the welfare implications of intellectual property protection appropriability, accounting for the multi-market structure of innovation on agricultural varieties.

3.1 Modeling appropriability and markets in the agricultural innovation process

A very specific characteristic of the the process of innovation on agricultural varieties is that, contrary to many innovation markets, where the innovator sells directly its innovation to the consumers on a single market, it is composed of two markets, and even three in the specific case of genetically engineered crops (Moschini and Lapan, 1997). The first market is specific to GM innovation, and is the market for the innovation, or, more precisely, for the introduction of the innovation into plant varieties. The actors of this market are the innovator and the crops suppliers (for instance, Monsanto and Delta&PineLand for the *Bt* cotton). The second market is the one for the improved variety, between the crops suppliers and the farmers. Finally, the third market is the one for the agricultural commodity, between the farmers and the final consumers. An equilibrium on the agricultural commodity market thus actually supposes an equilibrium on these two or three different sub-markets. This adds some challenge to the economic modeling of innovations on crop varieties, with respect to other types of innovation.

As noted by Lence et al. (2005), the existence of various markets between the innovation process and the consumption of the final product makes a welfare study slightly more complex than for evaluating innovations in other sectors. In particular, a welfare study should account for the consequences of an innovation on the welfare at each of the intermediary market. This is the major enhancement brought by Moschini and Lapan (1997) to the founding work of Griliches (1958) and the subsequent studies based on his model measured welfare variations that occur on the commodity market, following the development of new varieties. However, most models implemented to calculate the value of innovation from a social welfare point of view, even following the approach of Moschini et al. are still flawed, to some extent. First, they consider the capacity of the innovators to reap the benefits of their innovation is set once and for all by the legal framework. However, various factors actually determine the appropriability of the R&D outcome. Most models also do not account for the possibility that competitors of the innovator obtain a license to commercialize the innovation. Third, the welfare evaluations of crops innovation calculate the flow of surplus brought by the innovation. Such restriction is equivalent to an implicit assumption of stationarity in the different sub markets, although these evolve in time. They generally do not consider the value of innovation over its whole life span, from the early stages of research (accounting for duplication of R&D efforts) to the end of IP protection (accounting for the welfare gain caused by the increased competition on the market from then on). Lence et al. fill the last two gaps, at least to some extent. Their model assumed simultaneous equilibria on three markets (R&D, inputs and commodity). It also took into account the innovation race structure of the invention process.

In their model, Lence et al. (2005) assumed, first, that $n \in \mathbb{R}^{+*}$ R&D firms compete, in a patent race, to discover a new variety of crop. Second, once the innovation is discovered, it is commercialized to farmers, who can decide to adopt it or go on using traditional varieties. Finally, farmers produce the agricultural commodity and sell it to final consumers. In each step of this game, every player behaves to maximize its expected welfare. The discovery of the innovation is assumed to be *Hicks-neutral* (Hertel, 2012), *i.e.* to increase the total productivity of production factors. If $f(x, z)$ is the agricultural production function, where x is the quantity of seeds and z the quantity of other relevant inputs used, using the innovation changes the production function into $g(x, z) = \alpha f(x, z)$, $\alpha > 1$. The demand for agricultural output is a function $D(p)$ of the commodity price p. Consistently with the literature of games theory, the model is solved backwards.

Consider, first, the agricultural commodity market, which is assumed to be perfectly competitive. Denote ω_0 the endogenous price of the original variety, ω_1 the endogenous price of the new variety whenever it is available, and ω_z the exogenous price of other inputs. Define $\pi_0(p, \omega_0, \omega_z)$ the profit of farmers if they use the original variety, $\pi_1(p, \omega_1, \omega_z)$ the profit of farmers if they use the improved variety, and $\pi(p, \omega_0, \omega_1, \omega_z)$ the profit of the farmers if both technologies are available and they can choose between them,[17]. Denote $S(p)$ the supply function of the farmers, which is derived using Hotelling's lemma[18] the equilibrium quantity and price of agricultural output, y^* and p^* respectively, are defined by $y^* = S(p^*) = D(p^*)$.

Now turn to the input market equilibrium, and denote x_1^* the quantity of enhanced variety and x_0^* the quantity of original variety produced in the equilibrium. The first step is to compute the demand for the original and new variety, denoted

[17]Then, the expressions of π_0, π_1 and π are:

$$\pi_0(p, \omega_0, \omega_z) = \max_{x,z} [pf(x, z) - \omega_0 x - \omega_z z]$$

$$\pi_1(p, \omega_1, \omega_z) = \max_{x,z} [pg(x, z) - \omega_0 x - \omega_z z]$$

$$\pi(p, \omega_0, \omega_1, \omega_z) = \max \{\pi_0(p, \omega_0, \omega_z), \pi_1(p, \omega_1, \omega_z)\}$$

[18]Hotelling's lemma yields the expression for the supply function of the farmers, $S(p)$:

$$S(p) = \begin{cases} \partial\pi_0/\partial p \text{ if } \pi_0(p, \omega_0, \omega_z) > \pi_1(p, \omega_1, \omega_z) \\ \partial\pi_1/\partial p \text{ if } \pi_1(p, \omega_1, \omega_z) > \pi_0(p, \omega_0, \omega_z) \\ \text{a convex combination of } \partial\pi_0/\partial p \text{ and } \partial\pi_1/\partial p \text{ if if } \pi_0(p, \omega_0, \omega_z) = \pi_1(p, \omega_1, \omega_z) \end{cases}$$

x_0 and x_1 respectively. As was supply of the agricultural commodity, the demand for inputs for any given input prices ω_0 and ω_1 is easily derived using Hotelling's lemma.[19] One step backwards further lies the calculation of the supply of inputs by the producers of the original variety, and the improved one. The marginal cost of production of the enhanced and original varieties are c_1 and c_0 respectively. As an example, the analysis framework focuses on the case of perfectly competitive suppliers of original variety, which allows to derive the (inverse) supply function for the original variety easily: $\omega_0 = c_0$. The case of the new variety is more complex. To keep matters simple in the model presented here, assume that the innovation is drastic, *i.e.* it is sufficiently productive, compared to the original variety, to ensure that even when the producer of the new variety prices it as a monopolist.[20] However, the monopolistic power of the innovator is limited by the appropriability conferred by both the intellectual property protection system and the technological constraint that imitators would have to bear.

This is modeled by a parameter, μ_A that represents the maximal make-up that can be extracted (independently of its private optimal) by the innovator who discovered the new variety. This parameter represents the extra cost that a competitor would have to bear to replicate the innovation, in addition to its marginal cost of production. It has two components, $\mu_A = \mu_{IPP} + \mu_C$. The parameter μ_{IPP} represents the mark-up that is made possible by the granting and enforcement of intellectual property rights. It is thus equal to the expected fine if an imitator copies the innovation without the permission of the IPP holder.[21] The parameter μ_C represent the extra cost that an imitator would have to bear to imitate the enhanced variety, even if the innovator is not granted any IP right over the innovation (*e.g.*

[19]The expressions for x_0 abd x_1 are thus:

$$x_0(p,\omega_0,\omega_1,\omega_z) = \begin{cases} -\partial\pi_0/\partial\omega_0 \text{ if } \pi_0(p,\omega_0,r) > \pi_1(p,\omega_1,r) \\ 0 \text{ if } \pi_0(p,\omega_0,r) < \pi_1(p,\omega_1,r) \\ -\theta_0\pi_0/\partial\omega_0 \text{ if } \pi_0(p,\omega_0,r) = \pi_1(p,\omega_1,r), \theta_0 \text{ some parameter in } [0,1] \end{cases}$$

$$x_1(p,\omega_0,\omega_1,\omega_z) = \begin{cases} -\partial\pi_1/\partial\omega_1 \text{ if } \pi_1(p,\omega_1,r) > \pi_0(p,\omega_0,r) \\ 0 \text{ if } \pi_1(p,\omega_1,r) < \pi_0(p,\omega_0,r) \\ -\theta_1\pi_1/\partial\omega_0 \text{ if } \pi_0(p,\omega_0,r) = \pi_1(p,\omega_1,r), \theta_1 \text{ some parameter in } [0,1] \end{cases}$$

[20]Relaxing this assumption is easy. Indeed, following Moschini and Lapan (1997), it would only cause the price of the new variety to be capped by αc_0. However, this would make calculations quite heavier without significantly enhancing the model.

[21]If information is perfect and imitators are risk neutral, it is also equal to the licence fee that an imitator would negotiate with the IPP holder.

the cost of parallel research if the innovation is kept secret by the innovator). It is useful to exemplify the relative magnitudes of μ_{IPP} and μ_C for different types of innovation. In the case of hybrids, especially in the early 20$^{\text{th}}$ century, $\mu_{IPP} = 0$, because no institutional protection is granted to the breeders. The only source of appropriability is the secrecy over the parent lines of the improved variety. A similar reasoning applies to genetic use restriction technologies (GURTs) in countries, like India, that prohibit any IP protection to be granted over this type of varieties. In the case of a variety protected by a utility patent, the extra costs of imitation are almost negligible ($\mu_C \approx 0$), because the patent requires that the innovator discloses all information needed by a skilled man to manufacture the innovation. The marginal cost born by an imitator would thus be roughly similar to the one born by the innovator (plus, eventually, some sunk cost necessary to obtain the machines and systems of production). In that case, the only source of appropriability of the R&D outcome is the institutional protection, which requires an imitator to negotiate a licensing contract with the innovator, or to bear the risk of being sued for illegal copying. *A priori*, the value of μ_C is not constant in time,[22] but to keep matters simple, consider it is so. If the innovator sets a monopolistic price for the innovation ω_1^m (of course, so that the farmers prefer to buy the innovation rather than going on using the original variety, which is ensured by the assumption of drastic innovation) above $c_1 + \mu_A$, an imitator would make positive profits by imitating the innovation and selling it for any price between $c_1 + \mu_A$. Hence, the optimal pricing strategy of the innovator is:[23]

$$\omega_1 = \min\{\text{argmax}_{w_1}(w_1 - c_1)x_1[p(c_0, w_1, \omega_z), c_0, w_1, \omega_z], c_1 + \mu_A\}$$

The last step is to characterize the equilibrium in the R&D process. Like in most stochastic models of patent race, innovation is assumed to follow a Poisson process, and $n \in \mathbb{N}^*$ firms run for the innovation race. Lence et al. (2005) mixed the specifications of Loury (1979) and Lee and Wilde (1980) and specified that a firm $i \in [\![1, n]\!]$ spends both sunk costs k_i at the beginning of the race (which, they state, corresponds to capital investment), and a flow of costs throughout the race,

[22] For instance, as the other firms lead research in other fields, they get skills that may turn it cheaper to imitate the innovator. The process of production of the innovation may also become more publicly known, with the widespread of the innovation, retro-engineering may become less costly, etc.

[23] The first term in the argument of the minimum function is the unconstrained monopolist's pricing strategy, when the price for the original variety is c_0

l_i, as long as the race lasts which corresponds to labour costs). Firm i's hazard rate is then $h(k_i, l_i)$, and the industry-wide hazard rate is $H = \sum_{i=1}^{n} h(k_i, l_i)$. Firm i chooses both components of the intensity of its effort, k_i and l_i, to maximize its expected profit V (see appendix for the derivation of V):

$$V(k_i, l_i, H) = \frac{vh(k_i, l_i) - l_i}{r + H} - k_i \tag{5.36}$$

where r is the common discount rate, and v is the flow of payoff accruing to the innovator (see appendix for its expression). In symmetric equilibrium, each firm invests k^* in R&D sunk cost, and l^* in R&D cost flow.

Simulation. Lence et al. (2005) simulate the expected total surplus change induced by innovation, to establish a relationship between present value (at the beginning of the patent race) of welfare increase and appropriability level, as represented by parameter μ_A.[24] The definition of surplus used by Lence et al. is provided in appendix, and can be decomposed in consumers', farmers' and research firms' surplus. The curve, plotted on figure 5.1 has a bell shape up to a certain value of appropriability where it becomes flat. The bell shape part of the curve corresponds to the values of μ_A for which the innovator is constrained in its pricing strategy by the mark up made possible by the appropriability level. As μ_A increases, the innovator's expected profit, and simultaneously the incentive for innovation increases. The impact of an increase in μ_A on consumers' and farmers' welfare is more ambiguous. Conditional on the fact innovation is discovered, both decrease with μ_A (because the monopolistic power of the innovator allows it to capture more and more of the whole market welfare). However, an increase in μ_A encourages the innovator to intensify its research effort, making the innovation more likely to be discovered, and consumers' and farmers' welfare increase with the probability of discovery of innovation. Define $\bar{\mu_A}$ as the mark up that maximizes total welfare. For values of μ_A lower than $\bar{\mu_A}$) the present value of total welfare change increases with μ_A, because the effect of μ_A on innovators' profit and, hence, on the probability of innovation to be discovered outweighs the effect of the increased innovator's market power on instantaneous social surplus. For higher values of μ_A ($\hat{\mu_A} \leq \mu_A \leq \hat{\mu_A}$), the contrary

[24]In their simulation, they specify demand as a constant elasticity function: $D(p) = Dp^{-\varepsilon}$, a production function that ensures a constant elasticity supply function for farmers, and a constant elasticity of substitution (CES) production function and a Cobb-Douglas hazard rate $h(k, l) = Ak^{\kappa_K} l^{\kappa_L}$.

occurs: innovators' surplus increases and innovation is more likely to happen, but this is outweighed by the decrease in farmers' and consumers' welfare. For $\mu_A \geq \hat{\mu_A}$, the appropriability is not binding any more and expected variation in social welfare does not change with μ_A anymore. This is either because the monopolist's pricing is below $c_1 + \hat{\mu_A}$, or because if the innovator is constrained to price the new variety at $c_1 + \hat{\mu_A}$ because of the threat of other suppliers commercializing their own production of the innovation.

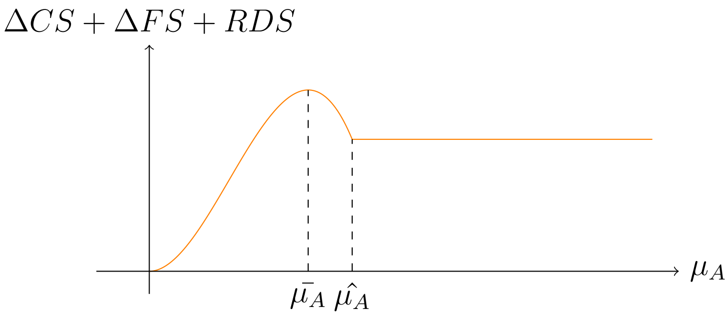


Figure 5.1: Shape of present value of expected change in total surplus as a function of appropriability level

An increase in the number of firms running for the patent race, n, has no impact on the appropriability threshold that releases the contraint on the price set by the IP rights holder ($\hat{\mu_A}$). This is normal, because this constraint only depends on what happens on the seeds market, once the innovation has been discovered. However, increasing the number of firms has two effects. First, it tends to stimulate firms in the IP race (if only one firm is running, it is sure to discover the innovation first, but if several firms are running they have an incentive to increase their effort to perform better than their competitors), which increases total expected welfare. Second, it makes duplication of effort more likely, which decreases total expected welfare. The first effect dominates for low appropriability, but the second effect dominates for high levels.[25] This result is quite likely to change if the model allows for subsequent innovations and takes into account the learning process of firms while they conduct R&D, even if it is unsuccessful: in this case, the duplication of research is less costly for R&D firms, because it provides research firms with experience for future research.

An larger elasticity of demand makes it harder for farmers and R&D firms to

[25]For $\mu_A \leq \bar{\mu_A}$, an increase in the number of firms increases the total expected welfare, and for $\mu_A \geq \hat{\mu_A}$, an increase in the number of firms decreases the total expected welfare.

extract rent from the consumers. Indeed, the consumers get less sensitive (in terms of welfare) to commodity price variations as elasticity of demand increases. They are thus less sensitive to the discovery of the improved variety, and a lower share of their welfare will be captured by other actors. Hence, whatever appropriability, an increase in elasticity of demand reduces total expected welfare. In the authors' simulations, the consumers' elasticity has no effect on the threshold appropriability $\hat{\mu_A}$. This is quite surprising, because it is very likely to modify the demand for seeds, and then the capacity of the monopolist to set a higher price when it is constrained neither by appropriability nor by the indifference of farmers for any of the generations of variety. As a decrease in elasticity of demand would decrease the monopolist's optimal pricing, the appropriability would thus be constraining on a smaller interval, and, if indifference of farmers was not binding, $\hat{\mu_A}$ would decrease consequently. To explain these observations, one may actually wonder whether the values of parameters used in the simulations are not so that whatever the studied values of demand elasticity, the new seed prices remain binded by the indifference of farmers.

Optimality of appropriability in the US seed industry. Lence et al. (2005) finally perform an analysis of the appropriability of hybrid seeds sold by the major US producer of such varieties, Pioneer Hi-Bred. Their model does not allow for a direct quantitative evaluation of what would be the optimal level of appropriability. Their strategy is thus to evaluate this level (by observing the average margin captured by Pioneer on their seeds), and to compute the parameters of the model so that this estimate of μ_A is optimal. They find that for the observed appropriability level to be optimal, the marginal productivity of factors (κ_K and κ_L) in the Cobb-Douglas hazard rate function should be both lower than 0.18. They conclude from this observation that appropriability on the hybrid seeds market in the US is probably insufficient.

Such result should however be subject to caution. First, the authors estimate the appropriability level in the US by measuring the gap μ_A^{est} between the market price of seeds and the marginal cost of production. However, first, imagine the case where the appropriability is not binding. Then, the monopolist sets a price that is lower than what it would be if the appropriability was binding (either because it sets the monopolist's price, or because it is constrained by the indifference of farmers between the original and the new varieties). What Lence et al. measure as appropriability will not be valid any more, and their estimate of appropriability would be underestimated. Second and more important, the authors assume a Cobb-Douglas hazard rate function, in which sunk cost are used to acquire capital, and variable costs are used to pay labour. This is a rather strong assumption (*e.g.* some of the capital is acquired and renewed throughout the research process), and hence identifying κ_K and κ_L to the respective marginal productivities of capital and labour is quite strong as well. Finally, more generally, although the authors state that the results of the model is not very sensitive to the value of the parameters, it is quite a stylized model, and concluding on quantitative results from it is probably ambitious.

3.2 Pest adaptation and innovation

Hueth and Regev (1974) first studied theoretically the optimal use of pesticides in presence of pest adaptation to pesticides. Their paper has been followed by many works, both theoretical and empirical (Carlson and Wetzstein, 1993). Two chapters in Laxminarayan (2003) extended the existing literature to take into account the structure of the agricultural market in their description of the development of pests resistance. Indeed, because inventors of new generations of pesticides are conferred IP protection over their innovation, the hypothesis that pesticides are competitively supplied is not often verified in practice.

Alix-García and Zilberman (2005) got one step further. They modeled the impact of the market power of the pesticide provider on the development of pests resistance, in a continuous time, dynamic optimization problem. Their model assumed that the demand function for pesticides is exogenous, decreasing with pest resistance. Pest resistance at a given time t depends on the record of past pesticides use: the speed of adaptation depends on current resistance level and the flow of pesticides use at this time. Using optimal control approach (cf chapter 5), Alix-Garcia and Zilberman determined the socially optimal path of pesticides use, and the market paths when the pesticide is provided by either a perfectly competitive market, or a monopolist. In a competitive market, they assumed the impact of pesticides on resistance build-up is not taken into account by pesticides producers. On the contrary, the monopolist does account for it, and thus faces a trade-off. It may supply more pesticides today (to increase present profits), but this will encourage a faster development of resistance (and thus lower demand for pesticides tomorrow). It may, otherwise, prefer to mitigate the development of resistance by providing less pesticides to the market, but, doing so, it will receive less profits today. Alix-Garcia and Zilberman found that when resistance develops fast enough, a competitive market results in too much pesticide use, and a monopoly results in too little pesticide use. This result is quite intuitive taking into account our previous remark. Because a competitive market does not take resistance into account, it will likely overprovide pesticides. When resistance builds-up fast, the monopolist will grant more importance to the future development of resistance, and will thus refrain from providing too much pesticides on short term to preserve future profits. Although improving pest adaptation models by accounting for the protection granted to innovation, the framework of Alix-Garcia and Zilberman did not account for the possibility for any actor to innovate, and discover a new generation of pesticides to which pests were less resistant than previous ones.

Goeschl and Swanson (2003) appears to have been the first study modeling agricultural innovation in presence of pests adaptation. They focused on innovation on plant varieties. They assumed that innovation and pests adaptation are discrete processes, and that both follow a Poisson process. Each step of innovation increases the total factor productivity of the production, while each step of adaptation reduces it.[26] In their model, a single firm innovates and chooses its R&D intensity, similarly to Loury (1979). Pests adapt to innovation at an exogenous pace. Goeschl and Swanson studied and compared the socially optimal R&D effort, and the monopolist's equilibrium R&D effort. They drew a relationship between pests' adaptation speed, and these two values of R&D intensity. Socially optimal research increases with pests adaptation speed, because a fast adapting nature makes all the more profitable to bear the costs of innovation to maintain, and even increase, agricultural production. On the contrary, the monopolist's equilibrium research decreases with adaptation speed, because a fast adapting nature reduces the expected profit extracted from innovation. Beyond some adaptation speed, private innovation is even led in vain, because the effect of innovation on production can never last long enough to make up for the costs of research. Hence, the curves of socially optimal and private investment intersect in a single point. In Goeschl and Swanson's model,

[26]Specifically, the production function when R&D has discovered $s \in \mathbb{N}$ innovations, and pests have adapted $p \in \mathbb{N}$ times by time t is $y_t = A_0 \gamma^{s-p} F(x_t)$, where y_t is agricultural output and x_t is the cultivated surface dedicated to output production at time t, A_0 and γ are positive parameters, and F is an $\mathbb{R}^+ \to \mathbb{R}^+$ function.

patents thus allow to attain social optimum by market equilibrium for a precise speed of pest resistance build-up only, and if adaptation speed is lower (respectively higher) than this threshold, the monopolist firm over invests (respectively under invests) in research. A major limit of Goeschl and Swanson's work is to assume that innovation is conducted by a single firm only. Such assumption is not equivalent to assuming implicitly that the IP regime is a full patent one, but it is much stronger. Indeed, even under patents other firms can conduct research on other in-bred lines, or other families of traits, different than those that are protected. It actually assumes implicitely that no other firm can compete, building its research on other varieties, which is stricter than any IP system existing across the world.

3.3 Comparing different regimes of intellectual property protection in agriculture

The different forms of intellectual property protection available for plant breeders have been detailed in chapter 3, and the relevance of differentiating them, because of the evolution of case-law since the early 2000s, has been questioned. In a very stylized manner, available IPP can be summarized as follows. On the one hand, *full patents* provide a strong protection that can hardly be infringed. On the other hand, *plant certificates* or *plant variety protections* (PVP) offer similar provisions in everything but two particular features. First, in most countries, they allow farmers to replant (and, in some countries, to even resell) the seeds they may save from their harvest. Second, and this difference will be used in this section, any firm may use almost freely protected material to improve it and develop subsequent new varieties. In this section we examine two papers belonging to the theoretical literature on the different available forms of intellectual protection property over plant innovation. Yerokhin and Moschini (2008) provided the first comparison of patents and PVP, when two firms compete for agricultural innovation in a context of pest adaptation. Lence et al. (2016) did not account for nature adaptation to innovation, but studied the implications of IP regimes in a more complete way than Yerokhin and Moschini, because they allow firms to use a share, that depends on the regime, of the stock of knowledge accumulated by their competitors.

Comparing IP regimes in presence of pests adaptation

Yerokhin and Moschini (2008) provided a model of sequential innovation to analyse the behavior of a duopoly under two regimes of IPR, full patents and PVPs. They assumed that, in a first stage, two firms can compete in a modified Loury (1979) model, in which innovation follows a Poisson process.[27] The first firm to innovate obtains the patent which drives an exogenous flow of profit until nature adapts. Adaption by nature is a Poisson process as well, of an exogenous hazard rate. Once nature has adapted, the flow of profit is reduced to zero, and a new patent race begins, which structure depends on the IP regime. Under PVP, both firms can take part in this new patent race. Under full patent, however, only the patentee firm can take part. The authors look for a Markov perfect equilibrium of mixed strategies (cf chapter 5).

The authors found that the best intellectual property protection regime, from a social welfare point of view, depends on the relative magnitude of the cost of R&D and the flow of profit accruing to the patentee. PVPs should be preferred when research cost is relatively low, and full patents should be preferred when research cost is relatively high, compared to the expected flow of profit accruing to the IP holder. This result is rather intuitive, because two effects are driven by protection level. On the one hand, under patent regime, winning the first race has a higher private value, and patents are thus a better incentive for firms to run for the patent race - which is beneficial to social welfare. However, on the other hand, patents prevent competition in the second patent race - which is detrimental to social welfare. Since research costs are exogenously set and independent of the protection regime, if they are high, firms will accept to invest only if they expect to extract a sufficient profit, and in that case the incentive for R&D investment is the main driving factor of social welfare. Thus, because patents lead to higher expected profits, they should be preferred. Indeed, the additional welfare allowed by PVPs in the second stage will be offset by the disincentive to invest in the first stage race it will cause. If costs are low, on the contrary, the regime of protection will not have a significant impact on the R&D investment decision of the firm. However, whether it allows competition in the second race will be decisive. The additional incentive brought by patent regime would be negligible against the cost caused by the reduction in

[27]Contrary to Loury, they assume R&D investment effort is exogenous, and firms decide whether they invest in R&D but cannot decide their effort's amplitude.

competition in the second stage they impose.

Yerokhin and Moschini provide a relatively simple model, however based on rather strong assumptions. First, they set a very constrained sequential innovation: the second innovation is necessarily built on the first one, and the race for the second patent cannot start until nature has actually adapted. It is true that it is probably easier to build on existing innovations to discover subsequent ones. However, considering that, under patent regime, the potential competitors cannot start from scratch to compete (eventually less efficiently) with the patentee is quite a strong assumption. Moreover, contrary to another assumption the model is based on, firms do not wait for nature to adapt to their innovation before they start searching for subsequent ones. For instance, Monsanto had developed new *Bt* varieties, in particular pyramidal ones, long before the first reports of adaptation were sent to the company. Second, they assume that, under PVP, in the second stage, firms can build research symmetrically on the innovation developed by the winner in the first stage. Yet, it is quite probable that the first inventor will have an advantage in working on its own lineages. Symmetry of firms in the second stage is, hence, probably a rather strong assumption, and relaxing it is likely to change slightly the conclusions of the paper. Indeed, this would increase the incentive of investing in the first stage race and probably makes the distinction between the two regimes less pregnant. Third, Yerokhin and Moschini also assume that nature adapts once and for all, reducing the value of the innovation to zero. However, in general, pests adaptation is a “continuous” process, progressively diminishing profits, and that the second patent race is assumed to be ran only when nature has adapted. Yet, for the patentee under patent regime, and for both firms under PVPs, the firms can start doing research as soon as the innovation is released, to be able to release the innovation immediately after nature adaptation. Finally, the model implicitly assumed infinitely lived protection. Yet, under patents, after the expiration of the first patent, if the first patentee has not developed another innovation, it is possible and potentially profitable for the other firm to enter the second stage race. The choice of protection regime is thus likely to drive timing strategies that are not addressed by this paper, and that would deserve attention.

Agricultural IP regimes and spillovers

Lence et al. (2016) provided a more general theoretical model of social comparison of intellectual property regimes, addressing some of the weaknesses of Yerokhin and Moschini (2008), although they do not allow to study the impact of pests adaptation. They studied the steady-state R&D investment level of an exogenous number $N \in \mathbb{N}^*$ of symmetrical firms, assuming a Nash symmetrical, pure-strategy equilibrium. They supposed that doing research has a cost, that depends positively on the R&D effort undertaken by the firm, and negatively by the stock of knowledge available to that firm at the considered moment. This stock of knowledge is composed of the total knowledge accumulated by the firm (discounted by a decay rate) thanks to its own past R&D programmes, and a share ω (which corresponds to the portion that is relevant for the firm) of the available knowledge accumulated by the other firms. The model is deterministic (cf chapter 5), and their proxy for the intellectual property protection regime is the lag with which one firm has access to the knowledge of all other firms. Under a PVP regime, knowledge available to a given firm i at any moment t is the sum of knowledge developed by all firms until time t. Under full patent of duration τ, knowledge available to firm i is the sum of the knowledge developed by all other firms until τ periods before t, plus the sum of knowledge developed by firm n up to period t. Under trade secret, knowledge available to firm i at time t is the knowledge of its own experience in development only. Hence, τ is not the protection length, but only the time for which information is not accessible to competitors (both are equal only for full patents and trade secrets).

The authors assumed innovation drives profit for a duration T, which represents the commercial life expectation of the innovated product.[28] They used numerical

[28]It is interesting to make clear the absence of link between τ and T, which is not made obvious by the article, as the authors distinguish the effect of IPR on subsequent research from its effect on appropriability of the monopolist's rent. τ represents the duration for which knowledge of a given firm is not accessible to other firms for further research. Hence it depends on the institutional framework of the intellectual property protection: PVPs make knowledge immediately accessible to other firms ($\tau_{PVP} = 0$); patents, if no research exemption, make it accessible only after patent expiration ($\tau_{patent} = \theta$, where θ is the patent duration), and well kept trade secret never makes is accessible ($\tau_{secret} = +\infty$). T represents the commercial lifetime of an invention, and thus depends on the market structure. For a non biotech good, on perfect markets and as long as following innovations are not substitues for the patented good, T is equal to the patent length. For biotech products, innovator's rent may be eroded by several factors (development of new pests, substitution innovations, climate and soil change, etc.). Hence, if we denote θ the protection duration, $T \leq \theta$ with equality if and only if θ is lower than commercial lifetime with an infinite protection. Yet, according to the literature (Barrows et al., 2014), average commercial lifetime of a biotech innovation is less than 10 years, hence much lower than patent/PVP duration which is around 20 years. Thus $T < \theta$ in most plants IPP frameworks. A link remains, however, between τ and T: the lower τ is, the faster competing innovations will be developed and hence the faster an innovation will be likely to be rendered obsolete.

simulations to compare the effect of the different IPP regimes on social welfare. To account for the link between T and τ, the authors set T, in the PVP scenario, to be significantly shorter than for the patent and trade secret ones. Two parameters vary to discuss the desirability of the regimes: the elasticity of research costs with respect to available knowledge (recall that research costs depend negatively on this knowledge), and the rate of decay. High elasticity corresponds to R&D projects that rely heavily on existing knowledge (the authors assume they correspond to more "complex" projects, such as "second-generation transgenes and the incorporation of exotic germplasm").

The authors first compared the investment effort under PVP and patents. At a given period t, three effects compete to trigger investment: the rent extracted by the monopolist (this effect is favored by patents), the reduction in costs triggered by relevant knowledge accumulated by the other firms between time $t - \tau$ and time t (this effect is favored by PVPs) and the reduction in costs triggered by the firm's own accumulated knowledge up to date t (which does not depend on the IPR). Hence, the optimal IPR results from a trade-off between the rent effect and the research exception effect. Obviously, when decay rate of knowledge is high, whatever the elasticity of costs with respect to available knowledge, the knowledge of other firms is useless. Then, the rent effect dominates and patents trigger more research than PVPs. When decay rate is low enough, the optimal regime depends on the elasticity of research costs with respect to available knowledge. If this elasticity is low, the effect of available knowledge on costs is not important enough, and, thus, the additional information available with PVPs does not overcome the additional rent offered by patents. If decay rate is low, patents then cause more research than PVPs. As elasticity increases, the opposite may begin to happen, and PVPs trigger more research than patents. If elasticity goes on increasing, the marginal effect of available knowledge on costs will increase as well, by definition. It may then happen that the firm's own knowledge reduce its costs to such an extent that the additional knowledge that PVPs will bring does not have a sufficient effect anymore to overcome the additional rent brought by patents, and hence patent become again the best generator of R&D effort.

The authors found that either PVP or patents can be the optimal IPR from a social point of view. When research programmes take a lot of time to outcome or when a technology is not easily transferable (which, according to the authors, correspond to transgenic plants research, which is quite developed in the US) patents should be preferred. When technology is easily transferable and research projects take less time (which corresponds to more traditional breeding techniques, that are more developed in Europe), PVPs drive more social surplus.

One may discuss, however, some of the assumptions the model of Lence et al. is developed on. First, the interpretation of the elasticity of cost with respect to available knowledge as a proxy for the type of research programmes (high elasticity corresponding to more complex, expensive programmes) would deserve further attention. Transgenic research probably requires more time and more investment, but it is not made clear that is takes more profit from past experience and from competitor's experience than more conventional breeding. More fundamentally, the authors compared two scenarios that differ in two different parameters (the patent scenario has both a higher rent duration T and a higher knowledge access lag τ), raising doubts about the relevance of the comparison. Indeed, it is not clear, when changing from patents to PVP, what is due to the increase in the rent period, and what is due to the decrease in the other firm's knowledge appropriation period.

3.4 Optimal R&D effort and IP protection on plant varieties in presence of environmental externalities

In the previous chapter, we saw that the study of research and development intensity, its socially optimal and market equilibrium levels, is an important sector of industrial economics. In section 2 this chapter, we reviewed some papers belonging to the wide scope of literature that studied the question of optimal protection over newly developed varieties. However, in the definition of optimality, such literature has not accounted for environmental concerns associated with innovation. Moreover, as we have discussed in chapter 1, innovation on varieties is not an integrated and uniform concept. As we showed in chapter 2, beyond the distinction of conventional and GM varieties, distinguishing the types of innovations, is crucial in discussing optimality of R&D effort.

Whether private firms conduct a sufficient and not excessive research effort, from a social point of view, has been a very rich question in industrial economics focusing on innovation dynamics. It has been investigated by several papers we have reviewed in the previous chapters such as Dasgupta and Stiglitz (1980) or Loury (1979). In the particular case of research on agricultural varieties, several more recent works have aimed at tackling this question (Goeschl and Swanson, 2003; Lence and Hayes, 2008). However, the discussions of optimality of private R&D effort should account for the externalities of the research process. Some studies have endeavored to take into account some of the externalities of agricultural research. (Griliches, 1991) did so in the general case of research and development activities. Several contributions, such as Huffman and Evenson (1993) and Rosegrant and Evenson (1993), have focused more precisely on spillovers among agricultural research firms. Finally, recent works have included the major role of spillovers and knowledge stocks among firms conducting research on plant varieties in their comparison of intellectual property regimes available for these firms (Lence and Hayes, 2008; Thomson, 2014; Lence et al., 2016). Nevertheless, other externalities of agricultural innovation are not not taken into account yet, including environmental ones. Because environmental externalities will change the optimal level of research, they will change the perspective on whether the private equilibrium R&D effort matches the optimum.

The eventual sub-optimality of R&D effort ask the question of adapting the existing framework of incentives for research, so that equilibrium R&D effort gets either matches the optimum, or, at least, gets closer to it. In the beginning of this chapter, we have reviewed some articles focusing on different aspects of this issue. The adaptation of intellectual protection system available for plant varieties has been an important field of research. In particular, in the sector of innovation on plant varieties, two regimes of intellectual protection may coexist (full patents and plant certificates) in addition to non-institutional protection (secrecy, GURTs, etc.). Several authors studied the conditions under which any of the institutional regimes is better than the other one. Lence et al. (2016) examined the proportion of research experience that should be made available to all firms, whatever their own experience. Yerokhin and Moschini (2008) compared the social welfare reached by patents and plant certificate, allowing for nature adaptation. However, no study discussed the optimal protection regime, accounting for broader environmental externalities of research. Positive externalities of research would call for more innovation - although it is not clear, *a priori*, which feature of IP regime (broader research exemption, prior user defense, etc.) would achieve such goal. This would deserve a more specific analysis.

Appendix

Loury (1979)

The probability that firm i wins the innovation between time t and $t+dt$ is given by:

$$\begin{aligned}
\Pr\left(W_i(t,dt)\right) &= \Pr\left(\{t<\tau_i\leq t+dt\}\cap\{t+dt<\tau_{-i}\}\right)\\
&= \Pr\left(t<\tau_i\leq t+dt\right)\Pr\left(t+dt<\tau_{-i}\right)\\
&= \Pr\left(t<\tau_i\leq t+dt\right)\prod_{j\neq i}\Pr\left(t+dt<\tau_j\right)\\
&= h(x_i)e^{-h(x_i)t}dt\prod_{j\neq i}e^{-h(x_j)(t+dt)}\\
&= h(x_i)e^{-h(x_i)t}dte^{-\sum_{j\neq i}h(x_j)(t+dt)}\\
&= h(x_i)e^{-\sum_{i=1}^{n}h(x_i)t}e^{-\sum_{j\neq i}h(x_j)dt}dt\\
&= h(x_i)e^{-\sum_{i=1}^{n}h(x_i)t}\left[1+\sum_{j\neq i}h(x_j)dt+o(dt)\right]dt\\
&= h(x_i)e^{-\sum_{i=1}^{n}h(x_i)t}dt+o(dt)=h(x_i)e^{-Ht}dt+o(t)
\end{aligned}$$

Then the expected profit of firm i at the beginning of the race is $V_i(x_i,H_{-i})$ is:

$$\begin{aligned}
V_i(x_i,H_{-i}) &= \int_0^{+\infty}\Pr\left(W_i(t,dt)\right)e^{-rt}\left(\int_0^T\pi e^{-r\theta}d\theta\right)-x_i\\
&= \int_0^{+\infty}h(x_i)e^{-Ht}e^{-rt}\frac{\pi}{r}\left(1-e^{-rT}\right)dt-x_i\\
&= \frac{h(x_i)\pi\left(1-e^{-rT}\right)}{r(H+r)}-x_i=\frac{h(x_i)\pi\left(1-e^{-rT}\right)}{r(h(x_i)+H_{-i}+r)}-x_i
\end{aligned}$$

Loury considered infinite patents only ($T=+\infty$), which gets:

$$V_i(x_i,H_{-i})=\frac{h(x_i)\pi}{r(h(x_i)+H_{-i}+r)}-x_i \tag{5.37}$$

It will be useful to note that a patent driving a flow of profit π for T units of time is exactly equivalent to an infinite patent driving an infinite flow of profit $\pi[1-\exp(-rT)]$. With infinite patents, the probability that firm i has won the patent race before time t is:

$$
\begin{aligned}
\Pr(W_i^b(t)) &= \Pr\left(\tau_i \leq \min(t, \tau_{-i})\right) \\
&= \Pr\left(\{\{\tau_i \leq t\} \cap \{t < \tau_{-i}\}\} \cup \{\{\tau_i \leq \tau_{-i}\} \cap \{\tau_{-i} \leq t\}\}\right) \\
&= \Pr\left(\{\tau_i \leq t\} \cap \{t < \tau_{-i}\}\right) + \int_0^t \Pr\left(\{\tau_i \leq s\} \cap \{s < \tau_{-i} \leq s + ds\}\right) \\
&= \left[1 - e^{-h(x_i)t}\right] e^{-H_{-i}t} + \int_0^t \sum_{j \neq i} \left[1 - e^{-h(x_i)s}\right] h(x_j) e^{-H_{-i}s} ds \\
&= \left[1 - e^{-h(x_i)t}\right] e^{-H_{-i}t} + H_{-i} \int_0^t \left[1 - e^{-h(x_i)s}\right] e^{-H_{-i}s} ds \\
&= \left[1 - e^{-Ht}\right] - \frac{H_{-i}}{H}\left[1 - e^{-Ht}\right] \\
&= \frac{h(x_i)}{H}\left[1 - e^{-Ht}\right]
\end{aligned}
$$

So, the expected profit of firm i is:

$$
\begin{aligned}
V_i(x_i, H_{-i}) &= \int_0^{+\infty} \Pr\left(W_i^b(t)\right) \pi e^{-rt} dt - x_i \\
&= \int_0^{+\infty} \frac{h(x_i)}{H}\left[1 - e^{-Ht}\right] \pi e^{-rt} dt - x_i \\
&= \frac{h(x_i)\pi}{rH} - \frac{h(x_i)\pi}{H(H+r)} - x_i \\
&= \frac{h(x_i)\pi(H+r) - h(x_i)\pi r}{rH(H+r)} - x_i \\
&= \frac{h(x_i)\pi}{r(H+r)} - x_i \\
&= \frac{h(x_i)\pi}{r(h(x_i) + H_{-i} + r)} - x_i
\end{aligned}
$$

And the expected innovation date across all firms is:

$$\begin{aligned}
\mathbb{E}(\tau) &= \mathbb{E}[\min(\tau_k)|_{k\in\{1,..,n\}}] \\
&= \int_0^{+\infty} t\Pr(t < \min_{k\in\{1,..,n\}}(\tau_k) \leq t+dt) \\
&= \int_0^{+\infty} t\Pr\left(\bigcup_{k=1}^{n}\{\{t<\tau_k\leq t+dt\}\cap\{t+dt<\tau_{-k}\}\}\right) \\
&= \int_0^{+\infty} t\sum_{k=1}^{n}\mathrm{h}(x_k)e^{-Ht}dt \\
&= \int_0^{+\infty} tHe^{-Ht}dt \\
&= \left[-te^{-Ht}\right]_0^{+\infty} + \int_0^{+\infty} e^{-Ht}dt \\
&= \frac{1}{\sum_{k=1}^{n} h(x_k)}
\end{aligned}$$

Hence:

$$\begin{aligned}
\frac{\partial\mathbb{E}(\tau)}{\partial n} &= -\frac{h(x^*)+nh'(x^*)\frac{\partial x^*}{\partial n}}{[nh(x^*)]^2} \\
&= -\frac{h(x^*)+nh'(x^*)\frac{\frac{\partial x_i^*}{\partial H_{-i}}h(x^*)}{1-\frac{\partial x_i^*}{\partial H_{-i}}(n-1)h'(x^*)}}{[nh(x^*)]^2} \\
&= -h(x^*)\frac{1-\frac{\partial x_i^*}{\partial H_{-i}}(n-1)h'(x^*)+\frac{\partial x_i^*}{\partial H_{-i}}nh'(x^*)}{\left[1-\frac{\partial x_i^*}{\partial H_{-i}}(n-1)h'(x^*)\right][nh(x^*)]^2} \\
&= -h(x^*)\frac{1+\frac{\partial x_i^*}{\partial H_{-i}}h'(x^*)}{\left[1-\frac{\partial x_i^*}{\partial H_{-i}}(n-1)h'(x^*)\right][nh(x^*)]^2}
\end{aligned}$$

Gallini (1992)

If the innovator choses to patent, any competitor can decide to imitate the innovation for a given cost K. The imitation cost is a dead weight loss (it does not accrue to any actor of the economy). Then, for the whole patent period T, the innovator and the $m \in \mathbb{N}^+$ imitators that have entered the market receive a common flow of profit, $\pi(m)$.[29] After the patent expires, the product is produced competitively and any profit vanishes. It is assumed that imitators enter the market as long as they (rationally) expect a positive profit. The number of imitators m entering the market is thus defined by the 0 expected profit relationship, where r is the common discount rate:

$$\left[\int_0^T \pi(m)e^{-rt}dt\right] - K = 0 \tag{5.38}$$

Hence, for a given patent length, $m > 0$ requires that the expected imitator's profit if an infinitesimal number of firms imitate is positive: $\int_0^T \pi(0)e^{-rt}dt - K > 0$. The patent length $T_I(K)$, that satisfies

$$\int_0^{T_I(K)} \pi(0)e^{-rt}dt - K = 0, \tag{5.39}$$

is thus the one for which imitators are indifferent between imitating and not imitating. Moreover, the expected profit of the patenting innovator is

$$\pi_i^p = \int_0^T \pi(m)e^{-rt} \tag{5.40}$$

It is useful to note that π_i^p is equal to K from the 0 expected profit (5.38), if and only if $m > 0$. The cost of imitation, K, reflects the breadth of a patent, set by the public policy - it also controls directly the profit of imitators, as these are assumed to enter the market until expected profits completely disappear. If the innovator chooses to keep the invention secret, two situations may occur. First, the innovation may remain secret, and this happens with a probability $1 - p_D$, the innovator gets indefinitely (not only for the patent duration) a monopolist's flow of profit, $\pi(0)$. In that case, the present value of expected profit is

$$\pi_i^s = \int_0^{+\infty} \pi(0)e^{-rt}dt = \pi(0)/r. \tag{5.41}$$

Second, the secret can be discovered, which happens with a probability p_D. It is then assumed that the secret is discovered at the moment the innovation is released. Then the innovation is produced competitively and neither the innovator nor the imitators receive any profit. Overall, the present value of expected profit if the innovator chooses to keep secrecy is thus $V^{NP} = (1 - p_D)\pi(0)/r$.

[29]Hence, the only difference between the innovator and the imitators is that the imitators have to pay the imitation cost K while the innovator does not.

If the imitation costs K are lower than the expected profit from keeping the innovation secret, *i.e.* if $K \leq V^{NP} = (1 - p_D)\pi(0)/r$, then it is profitable for the innovator to keep its invention secret. Indeed, if it is the case and the firm decides to patent, imitators will enter the market and the innovator's profit will be reduced to K from (5.38), which, by assumption, is lower than $(1 - p_D)\pi(0)/r$. If $T \leq T_I(V^{NP})$, it is more profitable for the innovator to keep its invention secret. Indeed, the innovator will prefer to keep innovation secret as long as patent duration, in the absence of imitation, drives less expected profit than secrecy. Yet, by definition of T_I, the patent duration for which the innovator is indifferent between patent and secrecy is precisely $T_I(V^{NP})$.

Henry (2010)

To begin with, compute the expected profit of the firms. First, define and compute the expected payoff of firm i if it is the first firm to innovate, $V_P(x_1, x_2)$, and the expected payoff of firm i if it is not the first firm to innovate, $V_F(x_1, x_2)$. Both values are discounted at the moment the first firm innovates (the choice of a Poisson process allows to do so easily, as the instantaneous probability of success conditional on no previous success, $h(x_i)$, does not depend on time). The payoff firm i will receive if it is the first one to innovate, $V_P(x_1, x_2)$, depends on the moment firm j innovates:

- If firm j finds the innovation between two times t_j and $t_j + dt_j$, $0 < t_j \leq T$, which happens with probability $\Pr(t_j < \tau_j < t_j + dt_j) = h(x_j)e^{-h(x_j)t_j}dt_j$, firm i receives π_m from 0 to t_j and π_d from t_j to L. The value at time 0 of this latter flow of profit, $\Pi_d(t_j)$, is:

$$\Pi_d(t_j) = \int_0^{t_j} \pi_m e^{-r\theta} d\theta + \int_{t_j}^{L} \pi_d e^{-r\theta} d\theta = \frac{\pi_m}{r}\left[1 - e^{-rt_j}\right] + \frac{\pi_d}{r}\left[e^{-rt_j} - e^{-rL}\right]$$

- If firm j finds the innovation between two times t_j and $t_j + dt_j$, $T < t_j$, which happens with probability $\Pr(t_j < \tau_j < t_j + dt_j) = h(x_j)e^{-h(x_j)t_j}dt_j$, firm i receives π_m from 0 to L. The value at time 0 of this latter flow of profit, Π_m, is:

$$\Pi_m = \int_0^{L} \pi_m e^{-r\theta} d\theta = \frac{\pi_m}{r}\left[1 - e^{-rL}\right]$$

Hence, expected payoff of firm i being the first one to innovate is:

$$\begin{aligned} V_P^i(x_1,x_2) &= \int_0^T \Pr(t_j<\tau_j<t_j+dt_j)\Pi_d(t_j)+\int_T^L \Pr(t_j<\tau_j<t_j+dt_j)\Pi_m \\ &= \frac{\pi_m-\pi_d e^{-rL}}{r}\left[1-e^{-h(x_j)T}\right]+\frac{\pi_d-\pi_m}{r}\frac{h(x_j)}{r+h(x_j)}\left[1-e^{-(r+h(x_j))T}\right] \\ &+\frac{\pi_m}{r}\left[1-e^{-rL}\right]\left[e^{-h(x_j)T}-e^{-h(x_j)L}\right] \end{aligned}$$

Similarly, the payoff firm i will receive if it is not the first one to innovate, $V_F(x_1,x_2)$, depends on the moment firm i innovates:

- If firm i finds the innovation between two times t_i and t_j+dt_i, $0<t_i\le T$, which happens with probability $\Pr(t_i<\tau_i<t_i+dt_i)=h(x_i)e^{-h(x_i)t_i}dt_i$, firm i receives nothing before t_i, and π_d from t_i to L. The value at time 0 of this latter flow of profit, $\Pi_F(t_i)$, is:

$$\Pi_F(t_i)=\int_{t_i}^L \pi_d e^{-r\theta}d\theta=\frac{\pi_d}{r}\left[e^{-rt_i}-e^{-rL}\right]$$

- If firm j finds the innovation between two times t_j and t_j+dt_j, $T<t_j$, it gets 0 profit.

Hence expected payoff of firm i not being the first one to innovate is:

$$\begin{aligned} V_F^i(x_1,x_2) &= \int_0^T \Pr(t_i<\tau_i<t_i+dt_i)\Pi_F(t_i) \\ &= \frac{\pi_d}{r}\frac{h(x_i)}{h(x_i)+r}\left[1-e^{-(h(x_i)+r)T}\right]-\frac{\pi_d}{r}e^{-rL}\left[1-e^{-h(x_i)T}\right] \end{aligned}$$

And, with $(V_F^i)'(x_i)=(\partial V_F^i/\partial x_i)(x_1,x_2)$:

$$\begin{aligned} (V_F^i)'(x_i) &= \int_0^T \frac{\pi_d}{r}\left[e^{-rt_i}-e^{-rL}\right]h'(x_i)\left[1-h(x_i)t_i\right]e^{-h(x_i)t_i}dt_i \\ &= \frac{\pi_d}{r}h'(x_i)\left[\frac{r\left[1-e^{-[h(x_i)+r]T}\right]+\left[h(x_i)^2T+rh(x_i)T\right]e^{-[h(x_i)+r]T}}{[h(x_i)+r]^2}\right. \\ &\left.+\frac{[1-h(x_i)T]e^{-[h(x_i)T+rL]}-e^{-[h(x_i)+r]T-rL}}{h(x_i)}\right] \end{aligned}$$

Hence, the expected payoff of firm i running the patent race is:

$$\begin{aligned}
V_i(x_1,x_2) &= \int_0^{+\infty} \Pr(\{t<\tau_i<t+dt\}\cap\{\tau_j>t+dr\})V_P^i(x_j) \\
&\quad +\Pr(\{t<\tau_j<t+dt\}\cap\{\tau_i>t+dr\})V_F^i(x_i) - x_i \\
&= \int_0^{+\infty} \left[h(x_i)V_P^i(x_j)+h(x_j)V_F^i(x_i)\right] e^{-[h(x_1)+h(x_2)+r]t} - x_i \\
&= \frac{h(x_i)V_P^i(x_j)+h(x_j)V_F^i(x_i)}{h(x_1)+h(x_2)+r} - x_i
\end{aligned}$$

The associated first order condition $\partial V_i/\partial x_i = 0$ is:

$$\frac{h'(x_i)\left[(h(x_j)+r)\,V_P^i(x_j)-h(x_j)V_F^i(x_i)\right]+h(x_j)(V_F^i)'(x_i)\left[h(x_1)+h(x_2)+r\right]}{\left[h(x_1)+h(x_2)+r\right]^2} = 1$$

Which is equivalent to:

$$\begin{aligned}
\frac{r\left[h(x_1)+h(x_2)+r\right]^2}{h'(x_i)} &= r\left[(h(x_j)+r)\,V_P^i(x_j)-h(x_j)V_F^i(x_i)\right] \\
&\quad +r\frac{h(x_j)}{h'(x_i)}(V_F^i)'(x_i)\left[h(x_1)+h(x_2)+r\right] \\
&= \pi_m\left[h(x_j)+r\right]\left[\left[1-e^{-h(x_j)T}\right]+\left[1-e^{-rL}\right]\left[e^{-h(x_j)T}-e^{-h(x_j)L}\right]\right] \\
&\quad +\left[\pi_d-\pi_m\right]h(x_j)\left[1-e^{-(r+h(x_j))T}\right] \\
&\quad +\pi_d\left[1-e^{-[h(x_i)+r]T}\right]\left[\frac{rh(x_j)\left[h(x_1)+h(x_2)+r\right]}{\left[h(x_i)+r\right]^2}-\frac{h(x_i)h(x_j)}{h(x_i)+r}\right] \\
&\quad +\pi_d T h(x_i)h(x_j)\frac{h(x_1)+h(x_2)+r}{h(x_i)+r}e^{-[h(x_i)+r]T} \\
&\quad +\pi_d h(x_j)e^{-rL}\left[1-e^{-h(x_i)T}\right]-\pi_d\left[h(x_j)+r\right]e^{-rL}\left[1-e^{-h(x_j)T}\right] \\
&\quad +\pi_d h(x_j)\left[\frac{[1-h(x_i)T]e^{-[h(x_i)T+rL]}-e^{-[h(x_i)+r]T-rL}}{h(x_i)}\right]\left[h(x_1)+h(x_2)+r\right]
\end{aligned}$$

In symmetrical equilibrium $x_1 = x_2 = x^*$, this condition becomes:

$$\begin{aligned}\frac{r\left[2h(x^*)+r\right]^2}{h'(x^*)} &= \pi_m\left[h(x^*)+r\right]\left[\left[1-e^{-h(x^*)T}\right]+\left[1-e^{-rL}\right]\left[e^{-h(x^*)T}-e^{-h(x^*)L}\right]\right]\\ &+\left[\pi_d-\pi_m\right]h(x^*)\left[1-e^{-(r+h(x^*))T}\right]\\ &+\pi_d\left[1-e^{-[h(x^*)+r]T}\right]\left[\frac{rh(x^*)\left[2h(x^*)+r\right]}{\left[h(x^*)+r\right]^2}-\frac{h^2(x^*)}{h(x^*)+r}\right]\\ &+\pi_d Th^2(x^*)\frac{2h(x^*)+r}{h(x^*)+r}e^{-[h(x^*)+r]T}-\pi_d re^{-rL}\left[1-e^{-h(x^*)T}\right]\\ &+\pi_d h(x^*)\left[\frac{[1-h(x^*)T]e^{-[h(x^*)T+rL]}-e^{-[h(x^*)+r]T-rL}}{h(x^*)}\right]\left[2h(x^*)+r\right]\end{aligned}$$

And assuming an infinite patent protection ($L \to +\infty$):

$$\begin{aligned}\frac{r\left[2h(x^*)+r\right]^2}{h'(x^*)} &= \pi_m\left[h(x^*)+r\right]+\left[\pi_d-\pi_m\right]h(x^*)\left[1-e^{-(r+h(x^*))T}\right]\\ &+\pi_d\left[1-e^{-[h(x^*)+r]T}\right]\left[\frac{rh(x^*)\left[2h(x^*)+r\right]}{\left[h(x^*)+r\right]^2}-\frac{h^2(x^*)}{h(x^*)+r}\right]\\ &+\pi_d Th^2(x^*)\frac{2h(x^*)+r}{h(x^*)+r}e^{-[h(x^*)+r]T}\end{aligned} \tag{5.42}$$

In $T = 0$, the first order condition is then:

$$\frac{h'(x^*)\left[h(x^*)+r\right]}{\left[2h(x^*)+r\right]^2}\frac{\pi_m}{r} = 1 \tag{5.43}$$

Differentiating totally the first order condition (5.42), collecting terms, and evaluating in $T = 0$, we get:

$$\frac{dx^*}{dT} = \frac{[\pi_m - 2\pi_d][r+h(x^*)]h(x)}{\pi_m h'(x) - r\frac{4[h'(x^*)]^2[2h(x^*)+r]-h''(x^*)[2h(x^*)+r]^2}{[h''(x^*)]^2}}$$

From (5.43):

$$\begin{aligned}\frac{dx^*}{dT} &= \frac{[\pi_m-2\pi_d][r+h(x^*)]h(x)}{r\frac{[2h(x^*)+r]^2}{h(x^*)+r}-4r\left[2h(x^*)+r\right]+r\frac{h''(x^*)}{[h'(x^*)]^2}\left[2h(x)+r\right]^2}\\ &= \frac{\left[h(x^*)+r\right][\pi_m-2\pi_d][r+h(x^*)]h(x)}{r\left[2h(x^*)+r\right]\left[-2h(x^*)-3r+r\left[h(x^*)+r\right]\frac{h''(x^*)}{[h'(x^*)]^2}\left[2h(x)+r\right]\right]}\end{aligned}$$

Since h is assumed to be concave, the denominator of this expression is negative. Hence, $dx^*/dT < 0$ if and only if $\pi_m > 2\pi_d$.

The condition for runner-up patents for being socially desirable is:

$$-\left[S_m - \pi_m\right]\left[\pi_m - 2\pi_d\right] + \pi_m\left[S_d - S_m\right] > 0$$

If $S_m > 2S_d$, then $\pi_m(S_d - S_m) > \pi_m S_m$ and $-\left[S_m - \pi_m\right]\left[\pi_m - 2\pi_d\right] + \pi_m\left[S_d - S_m\right] > 2S_m\pi_d + \pi_m^2 - 2\pi_m\pi_d$. Noting that it is necessary that $S_m > \pi_m$, we get that $-\left[S_m - \pi_m\right]\left[\pi_m - 2\pi_d\right] + \pi_m\left[S_d - S_m\right] > 0$.

If $S_m\left[r/\left[h(x^*) + r\right]\right] < \pi_m$, then:

$$\frac{S_m}{\pi_m}\frac{r}{h(x^*) + r} - 1 < 0$$

As $\partial x^* \partial T < 0$

$$\frac{\partial x^*}{\partial T}(0)\left[\frac{S_m}{\pi_m}\frac{r}{h(x^*) + r} - 1\right] > 0$$

As $S_d > S_m$ (duopoly is preferable to monopoly from a social welfare point of view):

$$\frac{dW}{dT}(0) = \frac{\partial x^*}{\partial T}(0)\left[\frac{S_m}{\pi_m}\frac{r}{h(x^*) + r} - 1\right] + \frac{S_d - S_m}{r}\frac{h^2(x^*)}{2h(x^*) + r} > 0$$

where $W(T)$ is the social welfare expected at the beginning of the patent race when the patenting window lasts T units of time. Then a strictly positive patenting window is socially desirable.

It is easy to show that under monopolist with a linear demand $S_m = (3/2)\pi_m$, that under Cournot competition with a linear demand $\pi_d = (4/9)\pi_m$ and that $S_d = (16/9)\pi_m$. Then:

$$\begin{aligned} -\left[S_m - \pi_m\right]\left[\pi_m - 2\pi_d\right] + \pi_m\left[S_d - S_m\right] &= -\left[\frac{3}{2}\pi_m - \pi_m\right]\left[\pi_m - 2\frac{4}{9}\pi_m\right] \\ &\quad +\pi_m\left[\frac{16}{9}\pi_m - \frac{3}{2}\pi_m\right] \\ &= \frac{4}{18}\pi_m > 0 \end{aligned}$$

Lence et al. (2005)

Derivation of (5.36) . This appendix first briefly explains the derivation of the expression of welfare expressions (5.36). Once again, the standard way of solving the problem is to reason backwards, first computing the gain of the first firm to innovate, and then solving the patent race equilibrium. Set time $t = 0$ at the moment the innovator discovers the new variety. For the next T units of time (which corresponds to the IP protection period), the innovator be protected by the rights granted according with the IPP regime. This corresponds to an appropriability coefficient $\mu_A = \mu_{IPP} + \mu_C$. Once the protection expires, after T units of time, the IPP rights fade away, and the only extent to which the innovator can still appropriate the result of innovation because of duplication costs, and $\mu_A = \mu_C$. The expected value of discovering the innovation is thus:

$$\begin{aligned} v(\omega_0, c_1, \omega_z, \mu_{IPP}, \mu_C, T, r) &= \int_0^T \left[\left[(\omega_1 - c_1) x_1 \right] |_{\mu_A = \mu_{IPP} + \mu_C} \right] e^{-rt} dt \\ &\quad + \int_T^{+\infty} \left[\left[(\omega_1 - c_1) x_1 \right] |_{\mu_A = \mu_C} \right] e^{-rt} dt \\ &= \frac{1 - e^{-rT}}{r} \left[\left[(\omega_1 - c_1) x_1 \right] |_{\mu_A = \mu_{IPP} + \mu_C} \right] \\ &\quad + \frac{e^{-rT}}{r} \left[\left[(\omega_1 - c_1) x_1 \right] |_{\mu_A = \mu_C} \right] \end{aligned}$$

Now, it is possible to turn to the patent race equilibrium. Suppose n identical firms run for the IPP over the new variety, and look for a symmetric equilibrium. Firm i decides the sunk R&D effort k_i and the flow of effort l_i it undertakes, and the hazard rate of firm i's innovation process is then $h(k_i, l_i)$, with $\partial h / \partial k_i > 0$ and $\partial h / \partial l_i > 0$, and $h(0,0) = \lim_{k_i \to +\infty} \partial h / \partial k_i = \lim_{l_i \to +\infty} \partial h / \partial l_i = 0$. The reasoning explained in chapter 5 allows to derive the expected profit of firm i at the beginning of the patent race, with $H = \sum_{i=1}^{n} h_i(k_i, l_i)$:

$$\begin{aligned} V(k_i, l_i, H) &= \int_0^{+\infty} \left[v(\cdot) h_i e^{-rt} - \left(\int_0^t l_i e^{-r\tau} d\tau \right) H \right] e^{-Ht} dt - k_i \\ &= \frac{v(\cdot) h_i - l_i}{r + H} - k_i \end{aligned}$$

Welfare analysis . Now, we present the definition of welfare, and its different components, used by Lence and al. in their article. Total surplus variation caused by innovation is spread between consumers, farmers and innovators. The variation of welfare flow accruing to consumers from the moment the innovation is discovered is:

$$\delta w_c(p_0, p_1) = \int_{p_1}^{p_0} D(\phi) d\phi$$

where p_1 is the equilibrium price of the commodity after the innovation is discovered (with $\mu_A = \mu_{IPP} + \mu_C$ for the T first units of time, and $\mu_A = \mu_C$ afterwards), and p_0 the equilibrium price of the commodity when only the original variety is available. The total expected variation of consumers' welfare at the moment innovation is discovered is then:

$$\begin{aligned}
\Delta W_c &= \int_0^T \delta w_c \left(p_0, p_1|_{\mu_A=\mu_{IPP}+\mu_C}\right) e^{-r\tau} d\tau + \int_T^{+\infty} \delta w_c \left(p_0, p_1|_{\mu_A=\mu_C}\right) e^{-r\tau} d\tau \\
&= \int_0^T \left[\int_{p_1|_{\mu_A=\mu_{IPP}+\mu_C}}^{p_0} D(\phi) d\phi\right] e^{-r\tau} d\tau + \int_T^{+\infty} \left[\int_{p_1|_{\mu_A=\mu_C}}^{p_0} D(\phi) d\phi\right] e^{-r\tau} d\tau
\end{aligned}$$

Then, in order to derive the total expected consumers' welfare change at the beginning of the patent race, use a reasoning analogous to the one developed to compute the expected profit of an innovator in the patent race models.[30] The total expected increase in consumers' surplus at the beginning of the patent race is then:

$$\begin{aligned}
\Delta CS &= \int_0^{+\infty} \Delta W_c e^{-(r+H)t} dt \\
&= \int_0^{+\infty} \left\{ \int_0^T \left[\int_{p_1|_{\mu_A=\mu_{IPP}+\mu_C}}^{p_0} D(\phi) d\phi\right] e^{-r\tau} d\tau + \right. \\
&\quad \left. \int_T^{+\infty} \left[\int_{p_1|_{\mu_A=\mu_C}}^{p_0} D(\phi) d\phi\right] e^{-r\tau} d\tau \right\} H e^{-(r+H)t} dt \\
&= \frac{H}{r(r+H)} \left\{ \left(1 - e^{-rT}\right) \left[\int_{p_1|_{\mu_A=\mu_{IPP}+\mu_C}}^{p_0} D(\phi) d\phi\right] + e^{-rT} \left[\int_{p_1|_{\mu_A=\mu_C}}^{p_0} D(\phi) d\phi\right] \right\}
\end{aligned}$$

Similarly, the flow of profit increase accruing to farmers after the innovation is discovered is $\delta w_f = \pi_1 - \pi_0$, and comparable reasoning yields the following expression for total expected increase in farmers welfare:

$$\Delta FS = \frac{H\left[\left(1 - e^{-rT}\right) \pi_1|_{\mu_A=\mu_{IPP}+\mu_C} + e^{-rT} \pi_1|_{\mu_A=\mu_C} - \pi_0\right]}{r(r+H)}$$

[30] If the innovation is discovered between two instants t and $t + dt$, which happens with a probability $He^{-Ht}dt$, the total consumers' surplus increases instantaneously by ΔW_c, which discounted value is the $\Delta W_c e^{-rt}$.

Finally, surplus brought by innovation to R&D firms is n times the expected profit of one single firm:

$$RDS = nV\left[k^*, l^*, nh(k^*, l^*)\right]$$

Chapter 6

Model of patent race in presence of environmental effects

Abstract

Research and development (R&D) on agricultural varieties has played throughout the 20$^{\text{th}}$ century and will still play in the future a crucial role in meeting the food need of global population. New varieties, less sensitive to past adaptation of pests, change the reliance of agriculture on chemicals, and hence its environmental footprint. Existing literature has studied the social optimality of research undertaken by private firm in a context of nature adaptation, but such analysis has failed in taking environmental externalities of agricultural production into account. The objective of this paper is to investigate how environmental externalities of innovation change the condition under which private research effort matches the social optimum. We use a standard patent race model, in which we integrate environmental externalities, to compare market equilibrium and social optimum R&D efforts. We show that when nature adapts either slowly or very fast, the private sector tends to overinvest and hence the incentives for research should be low to mitigate private research dynamism. On the contrary, when nature adapts at an average rate, the private sector tends to underinvest, and thus incentives for research should be increased.

1 Literature review and motivation

Agricultural research and development (R&D), especially on plant varieties, has played a central role in the revolution of agriculture throughout the 20$^{\text{th}}$ century. For example, the development of hybrids, followed by changes in intellectual protection over plants from the 1970s, have put an end to the thousand-years practice of replanting a share of harvested seeds. Genetical engineering changed the way farmers use chemicals: insect resistant (*Bt*) and herbicide tolerant (glyphosate and glufosinate tolerant) varieties have allowed farmers to reduce pesticides use (Qaim, 2009) and to use less toxic pesticides (National Research Council, 2010) respectively. Today, agricultural R&D remains a key determinant of agriculture's future. It lies at the core of one major global social stake of the 21$^{\text{st}}$ century: after having allowed large yields increases during the past century (Alston et al., 2010), it will have a crucial role in ensuring food security for 10 billion people by 2050 (Waggoner, 1995; Tilman et al., 2002). In addition, private companies have become the main source of R&D effort, because agricultural research offers significant perspectives of profitability (Pardey et al., 2014). Hence, R&D on varieties lies at the interface between a major social objective and private interests. In this context, matching the market outcome and social optimum of agricultural R&D is a central issue.

Achieving such goal is challenged by the fact that agricultural R&D meets the characteristics of a public good: it is non rival and, in the absence of intellectual protection systems, non excludable. As a consequence, innovation is under-provided by a competitive sector in the absence of relevant regulations and protection. Intellectual protection regimes have thus been implemented for this purpose. Two regimes of intellectual protection, first conceived to be exclusive from each other, but increasingly combined, are available for agricultural innovation: patent and plant variety protection (PVP). PVP has been the most commonly available protection for crops innovation worldwide, but since the early 1980s starting in the US (with the famous supreme court decision *Chakrabarty*) and spreading progressively to many other countries, utility patents over plants have been more and more accepted. The major difference between them is that the PVP provides a research exemption, *i.e.* it allows other inventors to conduct research on protected plants and commercialize the outcome without any agreement from the protection holder, while the patent does not, and requires a license agreement for any research conducted on a protected product. Yerokhin and Moschini (2008) have studied the optimal choice between the two different regimes. They build a model of sequential innovation in which two firms compete in a patent race to discover new varieties that yields a flow of profit. The sequential nature of the model can be described as follows. In a first race, research firms compete to discover a new variety which is rewarded by a flow of profit that is driven by the commercialization of the new crop. The flow of profit is earned by the innovator, until it is reduced to zero by adaptation of nature (for instance, by the development of pest resistance). Only once nature has adapted, the research process for a second variety, insensitive to nature's adaptation, can start. It is assumed that the subsequent innovation builds on the results of the previous one. Hence, under a PVP regime, both firms can compete to discover it, while under a patent regime, only the first innovator is able to develop a second innovation. By comparing the social welfare expected in each case, Yerokhin and Moschini found that a patent regime should be preferred when the cost of research is high compared to expected profits. The intuition behind this result is rather straightforward. It is necessary to provide more incentives for innovation to firms when research costs are high, otherwise no firm conducts research, and deadweight loss is a lesser evil than no research at all. Yet, full patent, despite increased social deadweight loss, drives higher incentives than research exemption, because it makes more likely for the innovator the possibility to capture the returns of subsequent innovations.

An optimal intellectual protection regime aims to balance incentives for research (the monopolist's rent it provides) and market distortions (the higher prices and lower quantities offered by a monopolist), and its optimal design deserves a special attention. An extensive literature on innovation has focused on intellectual protection and its efficiency, especially on its design to make private equilibrium match social optimum. Loury (1979) explored the question of socially optimal patent duration when several firms compete to innovate. In his model, innovation follows a Poisson process, and each firm chooses its R&D effort, this is the hazard rate of its innovation process. He analyzed the equilibrium effort undertaken by symmetrical firms (for either an exogenous or a zero profit endogenous number or firms), and compared it with a socially desirable R&D investment. He found that infinite patent duration lead to an over-investment by private firms. Therefore, he concluded that a finite patent duration can make the market equilibrium effort equal the socially desirable one. This finding is particularly interesting in the case of agricultural innovation, where infinite patent life is *de facto* impossible, whatever the legal framework. Indeed, when a new variety is discovered, nature reacts and pests adapt to the new variety developing resistance. The innovated variety's advantage over its competitors is thus progressively eroded, and, thus, innovator's rent decreases. On average, agricultural innovation lifespan is acknowledged to fall between 5 and 7 years (Goeschl and Swanson, 2003). Hence, whatever the patent duration, nature adaptation decreases incentive to innovate and thus the research effort of private firms. When the order of magnitude of optimal patent duration is close to innovation lifespan due to adaptation, even a longer than optimal legal duration of intellectual property will not result in a sub-optimal private investment in R&D. Indeed, legal duration of protection will not be a biding constraint for research firms.

In such context of nature adaptation, Goeschl and Swanson (2003) investigated whether patents allow to reach a desirable investment in innovation. In their model, a single firm innovates and nature adapts at a given speed. They drew a relationship between the speed of adaptation and the private and socially desirable investment efforts. They concluded that optimum investment increases with adaptation speed (nature adaptation makes innovation obsolete, hence the faster nature adapts, the stronger R&D effort should be to make up for obsolescence), while private investment decreases with adaptation speed. Moreover, patents allow to attain social optimum by market equilibrium for a precise nature adaptation speed only: while adaptation speed is lower (respectively higher) than this boundary, the monopolist firm over invests (respectively under invests) in research.

In addition to Goeschl and Swanson's specification, we point out another characteristic of agricultural innovation, namely its environmental externalities. Agricultural innovation has significant environmental impacts, both positive and negative. For instance, on the positive side, the adoption of insect resistant and herbicide plants has allowed a reduction in pesticides use and the toxicity of pesticides spread, respectively Qaim (2009). More generally, enhanced techniques and machines have allowed to use inputs more efficiently, and thus to reduce the environmental footprint of agriculture (Khanna and Zilberman, 1997). As examples of negative externalities, one may quote the fact that innovation accelerates the adaptation of pests and thus threatens the value of existing and future innovations - although, in the case of insect resistant crops, this issue has been tackled, at least partially, by integrated pest management strategies. Another example, in the case of GM varieties, is the risk of gene flow with uncertain consequences. The National Research Council (2010) provides a review of environmental impacts of genetically engineered crops on the environment, which tend to conclude that the overall effect appears to be rather positive. Such externalities of innovation are, of course, not taken into account by innovators, and is quite likely to modify the conditions under which private and social optimum meet.

In this paper, we propose to investigate the following questions. How do the externalities of innovation on the environment shift the social optimum? How does this shift modifies the conditions under which patents yield a social optimum? We will restrict our analysis to innovation on agricultural varieties. Moreover, we will consider that overall, at least in the period of time that follows such innovation, its environmental externality is positive. After the introduction of the new varieties, negative externalities of agriculture get more and more pregnant: reacting to nature adaptation, farmers modify the mix of inputs and rely on more and/or more toxic pesticides. Like Goeschl and Swanson (2003), we assume nature adapts to innovation. However, while their model focuses on a single innovating firm, ours is based on a competition of research firms that aim to discover new varieties, protected by an intellectual protection regime, as in Loury (1979) and Lee and Wilde (1980). We then compare the private equilibrium R&D effort and the socially desirable one.

2 The model

2.1 Duopoly R&D effort

Following Lee and Wilde (1980), consider two firms, denoted 1 and 2, running for a patent race in continuous time. Innovation is discrete, and, resulting of a Poisson process, is also memoryless.[1] Hence, the instantaneous probability of discovering the innovation knowing it has not been discovered before is constant, and does not increase with time. Their objective in the patent race is to develop a new variety of crops that is insensitive to existing pests. The parameter of the Poisson process of firm i, h_i, represents the R&D effort of this firm. If we denote $\tau_i \in \mathbb{R}^+$ the time of innovation of firm i (for simplicity, we assume that the new product starts being marketed immediately after it is discovered, so τ_i is also the moment firm i starts

[1]Adopting such representation for innovation process has been quite usual in the literature (Loury, 1979; Lee and Wilde, 1980; Reinganum, 1982; Henry, 2010).

to receive the flow of profit if it is the first firm to discover the innovation), then $\Pr(\tau_i > t) = e^{-h_i t}$. Like Loury (1979), we assume no R&D spillover across firms and no external incentives for innovation correlated across firms, which ensures that the occurence of innovation of both firms are independent. R&D requires a cost flow $c_i(h_i)$ to be incurred. Once an innovation is discovered, the innovator is granted a patent over it and captures a flow of monopolist's rent π. We assume patents are infinitely lived.[2] From this moment on, nature begins trying to adapt to the new variety.

We assume adaptation may occur in two different ways. The first way, called "weak adaptation", only obliges the farmers to spread more pesticides on cultivations, and does not alter the rent that can be extracted by the innovator (we assume that either the innovator commercializes the pesticides that allow to fight against weak adaptation of nature and produces it at 0 cost, or that the private costs of pesticides are negligible). We discuss this dimension in more details in the "social planner's" section as it has no impact on the research firms. The second way, called "strong adaptation" is similar to adaptation as modeled in Yerokhin and Moschini (2008). It makes the innovation obsolete and annihilates the extractable rent (we assume that the cost of mitigating strong adaptation for the producers is exactly equal to the profit extracted from the sale of the cultivation output). In this section, adaptation of nature always refers to strong adaptation. The strong adaptation follows a Poisson process of parameter $b \in \mathbb{R}^+$. The discount rate, r, is assumed constant across agents.

Once a firm becomes patentee, it stops doing research until either nature adapts or its competitor completes a new invention. Firms are engaged in a patent race, and, at any instant, firm i is either the patentee (if it is the last firm to have innovated and nature has not adapted yet), the challenger (if the other firm is the last firm to have innovated and nature has not adapted yet) or a duopolist (if nature has adapted after the last innovation). Whenever a firm's status changes, it adapts its R&D effort intensity decided once and for all until the next status change. We denote s the number of status changes (due to either invention or nature adaptation) before the observed status. Our model has thus many characteristics of a differential

[2]This one appears to be a rather strong assumption. However, patents and obtention certificates last in general at least 20 years, while, according to Barrows et al. (2014), commercial lifespan of an agricultural innovation, because of nature adaptation is around 10 to 15 years. Hence, patent duration is not binding and an assumption of infinitely-lived patents is not so unrealistic.

game (Dockner et al., 2000): we adopt a continuous time approach, and the hazard rate of firm is a payoff-relevant state variable. However, since we impose firms rather decide once and for all their strategy at each status change and the decisions of investment cannot be continuously adjusted, our model is a sequential dynamic game. Our assumptions allow us solve the model as if it was a sequential stationary game, which simplifies considerably the calculations. Denoting V_{pi}^s, V_{ci}^s and V_{di}^s the discounted payoffs for firm i being, respectively, the patentee, the challenger and a duopolist in the patent race at the beginning of a new status s, and h_{pi}^s, h_{ci}^s and h_{di}^s the associated efforts, one gets the following relations:[3]

$$rV_{pi}^s = \pi + h_{cj}^s \left(V_{ci}^{s+1} - V_{pi}^s\right) + b\left(V_{di}^{s+1} - V_{pi}^s\right) \quad (6.1)$$

$$rV_{ci}^s = h_{ci}^s \left(V_{pi}^{s+1} - V_{ci}^s\right) + b\left(V_{di}^{s+1} - V_{ci}^s\right) - c(h_{ci}^s) \quad (6.2)$$

$$rV_{di}^s = h_{di}^s \left(V_{pi}^{s+1} - V_{di}^s\right) + h_{dj}^s\left(V_{ci}^{s+1} - V_{di}^s\right) - c(h_{di}^s) \quad (6.3)$$

These are standard Bellman equations. The LHS of each equation, rV_{ji}^s ($j \in \{p, c, d\}$) is the instantaneous return on being in state j for firm i, since r is the interest rate. The first equation states that the instantaneous return on being the patentee must be equal to the flow of profit that accrues to the patentee, plus the expected loss in value caused by the possible changes in state. Indeed, h_{cj}^s and b are the instantaneous probabilities that firm i, being the patentee, becomes challenger (if the other firm innovates) or a duopolist (if nature adapts), respectively. The differences $V_{ci}^{s+1} - V_{pi}^s$ and $V_{di}^{s+1} - V_{pi}^s$ are the associated losses in value, respectively. A similar interpretation can be made for (6.2) and (6.3).

We look for Nash equilibria. Hence, when firm i is challenger, it chooses effort h_{ci}^s to maximize V_{ci}^s taking the $s+1^{\text{th}}$ payoffs as given, and when it is duopolist, it chooses effort h_{di}^s to maximize V_{di}^s taking h_{dj}^s and the $s+1^{\text{th}}$ payoffs as given. This yields the following first order conditions from differentiating (6.2) and (6.3) with respect to h_{ci}^s and h_{di}^s respectively:

$$c'(h_{ci}^s) = V_{pi}^{s+1} - V_{ci}^s \quad (6.4)$$

$$c'(h_{di}^s) = V_{pi}^{s+1} - V_{di}^s \quad (6.5)$$

Manipulating these equations, and assuming steady state and a symmetrical Nash

[3] See appendix “Duopoly” for the derivation of these equations.

equilibrium yield:[4]

$$\pi + c(h_c) = (r + 2h_c + b)\, c'(h_c) \tag{6.6}$$
$$\pi + c(h_d) = (r + 2h_d + b)c'(h_d) + (h_c - h_d)\, c'(h_c) \tag{6.7}$$

In order to give an expression for the optimal effort of the challenger, h_c^*, and a duopolist, h_d^*, we specify $c(x) = cx^2/2$, with $c \in \mathbb{R}^+$ a parameter. Then (6.6) and (6.7) can be written, respectively:

$$3c\,(h_c)^2 + 2(b+r)ch_c - 2\pi = 0 \tag{6.8}$$
$$3c\,(h_d)^2 + 2(b+r)ch_d - 2\pi + 2c(h_c - h_d)d_c = 0 \tag{6.9}$$

Solving these equations yields the same R&D effort undertaken by a private firm, when it is both a challenger and a duopolist:[5]

$$h_c^* = h_d^* = \frac{\sqrt{(r+b)^2c^2 + 6c\pi} - (r+b)c}{3c}$$

We thus obtain the following:

Proposition 1: Research effort increases with the flow of profit π accruing to the patent holder, and decreases with the speed of nature adaptation b.

This result is intuitive. First, a higher expected flow of profits makes it all the more desirable for a firm to become a new patentee. Second, the faster nature adapts, the shorter the expected period during which the researching firm may expect to receive profits if it discovers a new step of innovation.

It is interesting to note that $h_c^* = h_d^*$. This equality is the result of an exact balance of two forces. When the firm is a duopolist, its research effort is incentivized by the threat that its competitor wins the race before it. On would thus expect the duopolist to conduct research more intensively. However, precisely because of that threat, the payoff expected by a duopolist for a given intensity of research effort is reduced with respect to the expected payoff if it is a challenger and conducts research alone. This second effect of competition perfectly offsets the one we first

[4] The details of the calculations are presented in appendix "Duopoly".

[5] We have supposed so far that the firms actually take part in the patent race. This happens only if $V_c \geq 0$, which is equivalent to $\pi \geq (r+b)^2/2$ (cf. appendix). It ensures, as well, that $V_p \geq 0$.

mentioned.

2.2 Social planner's R&D effort

Weak adaptation of nature requires agricultural producers to increase their use of chemicals. We have supposed this has no effect on the private profit of the R&D firms, and is thus not internalized at all by these private actors, but the negative externalities caused by pesticides reduce the social welfare. We assume that when an innovation is discovered, the flow of social surplus is restored to a constant value $\omega \geq \pi$. We suppose that nature weakly adapts following a Poisson process of parameter γ. Each time nature adapts, the flow of social surplus is divided by $\alpha > 1$, *i.e.* if nature has adapted n times before time t, the flow of social surplus at time t is $w(t) = \omega/\alpha^n$. The variable $\omega(t)$ captures the profit of the innovators, the consumers' welfare derived from consumption of the agricultural good, and the negative externality of chemicals use, which erodes the welfares further each times nature weakly adapts.

If nature adapts strongly, before a new innovation is discovered, the only solution for the social planner to maintain the production is to apply a high level of pesticides. The flow of social surplus is then constant and negative, equal to $-\theta$ with $\theta \in \mathbb{R}^+$. We keep the same specification as in the previous section, considering it from the point of view of the social planner: at any moment, either it holds a valuable innovation (*i.e.* nature has not adapted since the last innovation) or it does not (*i.e.* the social planner has not found an innovation since the last adaptation of nature). Hence, there are only 2 possible states for the social planner: either holder of innovation, or not. By analogy with the previous section, we denote $\mathcal{V}_p^s$ the continuation payment for the social planner at the moment it innovates, and $\mathcal{V}_c^s$ the continuation payment at the moment nature adapts. We denote η_p^s the R&D effort of the social planner before nature's adaptation, and η_d^s its effort after nature has adapted. We assume that, after nature has strongly adapted, the former can spread its R&D activity between two research centers, so that it is not penalized by the assumed increasing marginal costs of the cost function. Such assumption is made in order to compare social planner's and private firms' optima. Then, the expressions for $\mathcal{V}_p^s$ and $\mathcal{V}_c^s$ are:[6]

$$\mathcal{V}_p^s(\eta_p^s) = \frac{\omega}{r+b+\beta+\eta_p^s} + \frac{\eta_p^s\mathcal{V}_p^{s+1} + b\mathcal{V}_d^{s+1} - c(\eta_p^s)}{r+b+\eta_p^s} \tag{6.10}$$

$$\mathcal{V}_d^s(\eta_d^s) = \frac{\eta_d^s\mathcal{V}_p^{s+1} - \left[2c\left(\frac{\eta_d^s}{2}\right)+\theta\right]}{r+\eta_d^s} \tag{6.11}$$

First order conditions yield:

$$c'(\eta_p^s) = \mathcal{V}_p^{s+1} - \mathcal{V}_p^s + \frac{\beta\omega}{(r+b+\beta+\eta_p^s)^2} \tag{6.12}$$

$$c'\left(\frac{\eta_d^s}{2}\right) = \mathcal{V}_p^{s+1} - \mathcal{V}_d^s \tag{6.13}$$

The socially optimal R&D effort after innovation is then:[7]

$$\eta_p^* = \frac{(r+b+\beta)^2}{3\rho} + \frac{1}{3}\rho - \frac{2}{3}(r+b+\beta)$$

where $\rho = \left((r+b+\beta)^3 + \frac{27\omega}{2c}\beta + \frac{3\sqrt{3}}{2}\sqrt{(\omega/c)\beta\left(4(r+b+\beta)^3+27(\omega/c)\beta\right)}\right)^{1/3}$.

Proposition 2: If nature does not weakly adapt ($\beta = 0$) or if it weakly adapts very fast ($\beta \to +\infty$), it is socially optimal not to conduct any research at all ($\eta_p^* = 0$). There exist two thresholds $\bar{\beta}$ and $\hat{\beta}$, $0 < \bar{\beta} < \hat{\beta} < +\infty$, so that for $\beta < \bar{\beta}$, the socially optimal R&D effort increases with β, and for $\beta > \hat{\beta}$, the socially optimal R&D effort decreases with β.

One may get the intuition behind the first part of this proposition (when $\beta = 0$) reminding we have assumed innovation $s+1$ does not create any social value *per se* compared to innovation s, it merely restores the initial value of innovation s. Hence, the only benefit from innovation is to offset the negative externality of pesticides use. Yet, if nature does not weakly adapts, there is no reason to apply pesticides. Thus, in that case, there is no incentive to innovate before nature strongly adapts.[8]

[6]See appendix "Social planner"

[7]See appendix "Social planner".

[8]On could think that even in that case a "preventive innovation", before nature adapts, would be desirable. This is not the case here, because we assumed strong adaptation follows a Poisson process. The instantaneous probability of adaptation thus does not depends on the time elapsed since last innovation. Hence, there is no benefit in innovating preventively, as the instantaneous probability that nature adapts before and after the innovation would be exactly the same.

The intuition behind the second part of the proposition ($\beta \to +\infty$) is that when nature adapts very fast, the social value of innovation vanishes quickly. In this case, whatever the environmental cost, the social planner abandons the competition against nature and spreads large amounts of pesticides. Then, the social planner has to resign to the fact that it is impossible to compete with nature. The remainder of the proposition is merely a consequence of these intuitions.

Proposition 3: If the environmental damage of pesticides is small compared to private profits, right after an innovation has been discovered, a duopoly always invests strictly more in R&D than socially optimal. However, if pesticides cause an important damage, there exist two thresholds β_1 and β_2, $0 < \beta_1 < \beta_2 < +\infty$ such that after an innovation has been discovered, if $\beta < \beta_1$ or $\beta > \beta_2$, the private duopoly to overinvests in R&D, and if $\beta_1 < \beta < \beta_2$ the private duopoly underinvests in R&D.

The first part of this proposition is rather straightforward. If the damage of pesticides is limited, before nature strongly adapts, the social benefit of innovation is very limited.[9] However, the competing firm still has an incentive to innovate, because it would benefit to take the place of the current innovator. Figure 6.1 illustrates the second part of this proposition, in the case where private underinvestment arises. For $\beta < \beta_1$ and $\beta > \beta_2$, firms in duopoly invest more in R&D than socially desirable immediately after an innovation is discovered. Such situation can be interpreted as a useless duplication of research, that outstrips beneficial environment impact of innovation. For $\beta_1 < \beta < \beta_2$, the duopolist's effort is lower than socially desirable. Then, the beneficial environmental impact of research more than makes up for the loss caused by duplication of efforts.

Now, we look for the socially optimal level of research after nature has strongly adapted, η_d^*. We restrict our study to the case where nature does not weakly adapt, *i.e.* $\beta = 0$. Using similar reasoning to the one developed in the Duopolist section, we get the socially optimal investment in R&D after nature has strongly adapted:[10]

$$\eta_d^* = \frac{\sqrt{(r+b)^2c^2 + 4c(\omega+\theta)} - (r+b)c}{c} \tag{6.14}$$

[9] In the polar case where the use of pesticide caused by weak adaptation has no environmental impact, there is no need to innovate from a social point of view as long as nature does not strongly adapt.

[10] The calculations are detailed in appendix ”Social planner”.

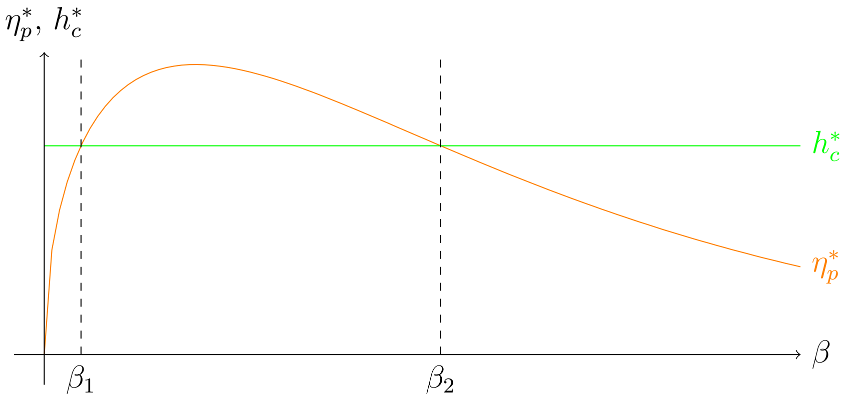


Figure 6.1: Comparison of social and duopoly optimal investment

Proposition 4: Consider nature has strongly adapted, and the specific case where nature does not adapt weakly. Duopolistic firms always underinvest in research compared to social optimum. In addition, the socially optimal investment in research increases with both the flow of social benefit before natures strongly adapt, and the flow of social cost afterwards.

The first part of this proposal can then be understood as follows. For the research firms, the incentives to innovate are weaker than for the social planner. Indeed, after the innovation is obsolete, the social planner will expect to earn more social welfare (ω) and to get rid of the social cost of the social cost of intensive pesticide use (θ). On the contrary, the private firms may only expect the flow of private profit (which is lower than the flow of social surplus, $\pi \leq \omega$), and do not bear any flow of cost before they innovate. Moreover, the value of the flow of profit expected by one firm is hampered by the threat of competition of its competitor.

The second part of this proposition is straightforward. Indeed, the more costly it is to have lost all value of innovation (after nature has strongly adapted), and the more profitable it is to hold a useful innovation (before nature has strongly adapted), then the most profitable it is to strive for innovation after nature has adapted.

2.3 Monopoly's R&D effort

To complement our study, it is interesting to consider the case of a single research firm operating as a monopolist. We still assume no weak adaptation of nature ($\beta = 0$). Keeping the same analytical framework to study a monopolist firm makes our assumptions even stronger, because it is poorly realistic that no research at all is conducted by the monopolist before nature strongly adapts. Yet, in our model, the monopolist does not expect any gain from innovating. However, such specification makes it possible to compare our results with existing literature. If only one firm it operating, it conduct research only after nature has strongly adapted, with intensity H^s to discover the s^{th} innovation. We thus get the following set of Bellman equations:[11]

$$r\mathcal{V}_p^s = \pi + b\left(\mathcal{V}_d^{s+1} - \mathcal{V}_p^s\right) \tag{6.15}$$

$$r\mathcal{V}_d^s(H) = H^s\left(\mathcal{V}_p^{s+1} - \mathcal{V}_d^s\right) - c(H^s) \tag{6.16}$$

The stationary equilibrium investment in R&D, H^*, is obtained as in the previous sections:

$$H^* = \frac{\sqrt{(r+b)^2c^2 + 2c\pi} - (r+b)c}{c} \tag{6.17}$$

Proposition 5: Assume nature does not weakly adapt. A monopolist always conducts more research than a duopolist firm, but less than the two duopolists together. It conducts less research than socially desirable if and only if the sum of social surplus and social cost flows before and after the strong adaptation of nature ($\omega+\theta$) are larger than a threshold $\bar{\omega}$. A monopoly is all the more likely to be socially desirable (with respect to duopoly) that research costs are large, and private profits are small.

Hence, if a monopolist firm operates on the market, and has the opportunity to invest in R&D only after nature has strongly adapted, it will invest more than what the duopolists would after nature's strong adaptation. Under this specification, on the one hand, the monopolist is no longer challenged by competition that encouraged it to invest in R&D after nature had adapted strongly. On the other hand, the expected profits from conducting research are higher, since the monopolist does not fear to have them captured by a competitor that would win the race.

Finally, if research costs are high before the expected flow of profits, a monopoly is more likely to be socially preferable than a duopoly.

[11] See "Monopolist firm" appendix for the derivation of the Bellman equations (6.15) and (6.16), the expression of H^*, and the results stated in this paragraph.

3 Discussion

3.1 Environmental effects in the innovation analysis framework

We have developed a theoretical model that complements the existing framework of analysis of social optimality in R&D investment in the agricultural sector. It aims to understand the underlying relationship between nature adaptation and R&D environmental impact, especially in order to take these aspects in consideration in policy design. Our objective is to highlight the importance of intellectual protection design and/or calibration of public support to agricultural research in presence of environmental externalities. In particular, we have shown that incentives and support for agricultural R&D should be designed taking into account the way nature adapts: for instance, if nature adapts very slowly, it would be preferable to moderate incentives to innovate.

Our first contribution is to shed some light on environmental effects in the discussion about optimal private R&D effort in the agricultural sector. We have stressed that in the presence of nature adaptation, taking into account the externalities of innovation on the environment has an influence on the comparison between private and social optimal research effort. As Goeschl and Swanson (2003), we find that the market optimum hardly matches the social one: only for some precise intensities of nature adaptation is private R&D effort in line with the social planner's objective. However, our results differ significantly from what Goeschel and Swanson found. They concluded that a private sector monopolist overinvests in R&D when nature adapts slowly, from no adaptation at all until a threshold speed of adaptation that matches private and social interests. While adaptation speed increases beyond this threshold, the private sector begins to underinvest, and the underinvestment gap increases with adaptation speed. We would expect the specificities of our model, compared to theirs, to have two opposite effects. Taking environmental externalities of research into account makes R&D more socially desirable, and would make underinvestment of firms more likely. On the contrary, the duopolistic structure of the market we assumed is likely to encourage competing firms to invest in R&D before nature adapts. When one of the firm is a challenger, it finds it profitable to invest in R&D to become the patentee, whereas, considering our assumption that innovation merely restores previous profit after nature has adapted, a private monopolist would not invest any effort in R&D before nature adapts. For low adaptation speed of nature, we find similar results, but obtain significant differences when nature adapts faster. In our model, indeed, as adaptation speed increases, private duopoly turns back to overinvestment.

Our second contribution is to complement the existing framework of analysis of the innovation process, in particular in a competitive environment. Our model acknowledges that competition for innovation may lead to welfare loss due to duplication of efforts, which is consistent with Loury (1979). However, despite the fact that duplication causes a net welfare loss when nature does not adapt often, if may actually help to compete with nature when the latter adapts faster. The case where nature does not weakly adapt ($\beta = 0$) makes our setting close to the one developed by Yerokhin and Moschini (2008). They built a model of agricultural innovation in duopoly using a Lee and Wilde (1980)-style model, though with a significant difference: they assume the level and cost of R&D effort is exogenously set, and the firms' decision variable is their probability to take part in the race. They consider only what we call strong adaptation, excluding any environmental externality. Their assumption on timing of innovation is even stronger than ours, assuming that no research at all can be conducted before nature (strongly) adapts. They specify two different R&D regimes. The first regime is full patent, in which only the first firm to invent is the only one able to conduct subsequent research. This is a very strong hypothesis to model full patent, because it does not only prevent competitors to work on the initial, protected innovation, but it also rules out any "external innovation", developed by the competitor to serve the same purpose, but based on different genetical resources it can work on. The second regime is research exemption, in which any firm can strive to develop any subsequent innovation. Our specification of monopoly corresponds to their definition of full patent, and our framework of duopoly corresponds to what they name research exemption.[12] Then, our model derives a result that is somehow close to Yerokhin and Moschini's conclusions: if research costs are high (especially before the expected flow of profits), a monopoly is more likely to be socially preferable than a duopoly.

[12]We claim, however, that it allows to study basically any regime, including full patent, in which patents are not infinitely broad, *i.e.* under which the possibility exists for a competitor to innovated based on its own or publicly available lines of plant varieties.

3.2 Policy implications for intellectual protection and public support to R&D

The conclusions of our model can be interpreted in the context of R&D policy. They shed some new light on the determinants of an optimal IP regime and/or public support to R&D, supporting the idea that speed of nature adaptation is an important characteristic. The literature has long focused on the optimality of universal IP regimes, and has shown that a "one size fits all" instrument in IP is rarely feasible in intellectual protection policies. For instance, Hopenhayn and Mitchell (2001) show that a menu of different combinations of patent breadth and length should be proposed to sort innovations that differ in potential subsequent innovations. We show that the IP policy should modulate incentives for innovation with potential adaptation speed of nature. Our conclusions thus question further the current IP systems. Indeed, these systems offer protection for a universal period of time, across the sectors of innovation. However, our results support the idea that optimal protection systems should be tailored to fit each particular sector of research. Intellectual protection should be looser, *i.e.* should last shorter and be of tighter breadth, in sectors of agricultural research where nature adaptation is either very slow or very fast. In between, intellectual protection should be stronger. Similarly, public R&D and public support to private R&D should focus on sectors where nature adaptation's speed is average.

The implementation of such recommendation would require the identification of adaptation speed that would be intrinsic to each innovation, depending on the pests it targets, and the region it will be planted in. It seems that such measures, that could help to specify further the prescriptions of our study, do not exist yet. Gathering such data would be quite a difficult exercise, because the speed of resistance build-up depends precisely on the quantity of pesticides that is faced by the pest. Hence, defining a scale of potential adaptation speed that could be used to rank research projects, is quite challenging. However, Roush and Tabashnik (1990) review several studies that show a significant heterogeneity in adaptation pace due to either geographical or genetical factors. Such finding tends to prove that across innovations, depending on the species of pest that one improved crop targets, or on the area of cultivation it is dedicated to, the speed of resistance build-up will vary significantly. It could then be either away from or between the two speed thresholds defined by our model, which legitimates our recommendations.

3.3 Perspectives

This research may lead to a number of possible extensions. A first direction would be to refine the study by specifying further the mechanisms taken into account and modeled. First, it would be interesting to relax some assumptions. One of our restrictive assumptions is that the consequence of an innovation is merely to restore the same situation as the one that prevailed upon the discovery of previous invention. One could consider the case in which the flow of private profits increase after each innovation. In such case, the argument of stationarity we used would not hold any more, but the model would fit more closely to the observed increasing profits in the agricultural R&D industry in the past years. Another assumption that could be relaxed is the duopoly restriction. As in Loury (1979), whether a certain number of firms in the research market could reach the socially optimal total research effort could be an interesting question to investigate. It would then be possible to compare this optimal number of firm with the one reached on a free entry market. Second, the way we modeled the innovation process and outcome could be improved. We did not consider differences across innovations. In particular, we did not account for differences in the magnitude of innovation, especially between breakthroughs and adaptations of well know processes, that require different intensities in R&D, levels of experience, and, eventually, access to protected previous innovations. For example, consider *Bt* crops. The discovery of the *Bt* gene, and of the process to insert it in plants has been based on intense research in the 1980s. In the competition to develop *Bt* crops, no biotech firm was particularly advantaged *ex ante*. The development of different variants of *Bt* traits (like Cry1A, Cry2Ab, etc.), or of varieties with stacked genes, may be considered as a sub-innovation. It used less R&D effort, but gave a significant advantage to firms that had already experience and held patents in the field of *Bt* over their competitors. Implanting the first *Bt* trait in different crops, after it had first been implanted in tobacco, required even less R&D effort but was practically possible for the firms that held patents over this trait (Charles, 2002). Accounting for such heterogeneity in firms and innovations would provide richer results.

A second possible direction would be to extend the model to account for some particular features of the innovation and adaptation processes. First, one could study the dynamic pattern of R&D investment (Reinganum, 1982). We have assumed in our study that the decision about the effort of R&D by either the private firms and the social planner is taken once for all at the beginning of each new innovation race. Yet, although a research programme is obviously planned *ex ante* over several years, dismissing any possibility of dynamic adjustment is a strong assumption. This simplifies considerably the calculations, but does not allow to study how firms strategically respond to each other throughout the innovation process. Second, it would be interesting to consider possible retroaction between the state of the environment and nature adaptation. In our model, we have supposed that the speed of adaptation of nature is exogenous and constant. However, the speed of adaptation of pests actually depends on the amount of pesticides spread over cultivated surfaces (Laxminarayan, 2003). The Poisson parameter of nature adaptation is thus likely not to be constant, but is rather increasing with time. Finally, a last direction would be to consider a stock effect in the environmental externality of agricultural production. Indeed, in our model we have assumed (once again in order to rely on stationarity arguments for simplification) that each innovation regenerates the flow of social welfare to its initial value. This is equivalent to assuming that the stock of chemicals previously used has no effects on either the present state of the environment or the adaptation speed of nature. Yet, the track record of past chemical use, more than its flow, has an impact on environment quality and nature adaptation, in a hysteresis phenomenon (Pimentel, 2009).

Appendix

Dupololy

A way to calculate the expected payoff of firm i after a status change is to observe each short period of time, between two close moments t and $t + dt$, for $t \in [0; +\infty]$. To begin with, consider that firm i is the current patentee, that nature has not (strongly) adapted yet, and set $t = 0$ at the moment the patentee innovates, and denote τ_n the moment nature adapts. Between t and $t + dt$, four situations may occur:

- The other firm has not innovated before and does not innovate during this period, and nature has not adapted before and does not adapt. In this case, firm i earns a flow of profit π during dt, and the discounted value of its income is

$e^{-rt}\pi dt$. This happens with a probability $p_1 = \Pr\left(\{t+dt < \tau_n\} \cap \{t+dt < \tau_j\}\right)$. Innovation and nature adaptation are supposed to be independent events, so:

$$\begin{aligned} p_1 &= \Pr\left(t+dt < \tau_n\right)\Pr\left(t+dt < \tau_j\right) \\ &= e^{-b(t+dt)}e^{-h^s_{cj}(t+dt)} \\ &= e^{-(b+h^s_{cj})t}e^{-(b+h^s_{cj})dt} \\ &= e^{-(b+h^s_{cj})t}\left[1-(b+h^s_{cj})dt + o(dt)\right] \end{aligned}$$

The last equality uses a Taylor expansion of exponential around 0.

- Nature has not adapted before and does not adapt during this period, and firm j innovates precisely between t and $t+dt$. In this case, firm i becomes the challenger of the next patent race, and hence receives the lump-sum continuation payment for being so, V^{s+1}_{ci}, which discounted value is $e^{-rt}V^{s+1}_c$. This happens with a probability $p_2 = \Pr\left(\{t < \tau_j \leq t+dt\} \cap \{t+dt < \tau_n\}\right)$. Because of independence:

$$\begin{aligned} p_2 &= \Pr\left(t < \tau_j \leq t+dt\right)\Pr\left(t+dt < \tau_n\right) \\ &= h^s_{cj}e^{-h^s_{cj}t}dte^{-b(t+dt)} \\ &= h^s_{cj}e^{-h^s_{cj}t}dte^{-bt}e^{-bdt} \\ &= h^s_{cj}e^{-(b+h^s_{cj})t}dt + o(dt) \end{aligned}$$

- Firm j has not innovated before and does not innovate during this period, and nature adapts precisely between t and $t+dt$. In this case, firm i joins firm j in a duopoly for the next patent race, and hence receives the lump-sum continuation payment for doing so, V^{s+1}_{di}, which discounted value is $e^{-rt}V^{s+1}_d$. This happens with a probability $p_3 = \Pr\left(\{t < \tau_n \leq t+dt\} \cap \{t+dt < \tau_j\}\right)$. Because of independence:

$$\begin{aligned} p_2 &= \Pr\left(t < \tau_j \leq t+dt\right)\Pr\left(t+dt < \tau_n\right) \\ &= be^{-bt}dte^{-h^s_{cj}(t+dt)} \\ &= be^{-bt}dte^{-h^s_{cj}t}e^{-h^s_{cj}dt} \\ &= be^{-(b+h^s_{cj})t}dt + o(dt) \end{aligned}$$

- If either firm j has innovated or nature has adapted before t, firm i gets nothing, and the probability that both nature adapts and firm j innovates between t and $t+dt$ is in dt^2 and thus negligible.

The total expected payoff for obtaining the patent is thus:

$$\begin{aligned} V_{pi}^s &= \int_0^{+\infty} \left[p_1 e^{-rt}\pi dt + p_2 e^{-rt} V_{ci}^{s+1} + p_3 e^{-rt} V_{di}^{s+1}\right] \\ &= \int_0^{+\infty} \left[\left[e^{-(b+h_{cj}^s)t}\left[1-(b+h_{cj}^s)dt + o(dt)\right]\right] e^{-rt}\pi dt\right. \\ &\quad \left. + \left[h_{cj}^s e^{-(b+h_{cj}^s)t} dt + o(dt)\right] e^{-rt} V_{ci}^{s+1} + \left[b e^{-(b+h_{cj}^s)t} dt + o(dt)\right] e^{-rt} V_{di}^{s+1}\right] \end{aligned}$$

Keeping first order terms only:

$$V_{pi}^s(h_{cj}^s) = \int_0^{+\infty} \left(\pi + h_{cj}^s V_{ci}^{s+1} + b V_{di}^{s+1}\right) e^{-(r+b+h_{cj}^s)t} dt$$

Hence:

$$V_{pi}^s(h_{cj}^s) = \frac{\pi + h_{cj}^s V_{ci}^{s+1} + b V_{di}^{s+1}}{r+b+h_{cj}^s} \tag{6.18}$$

Using a similar reasoning,[13] we get the following expression for V_{ci}^s and V_{di}^s:

$$V_{ci}^s(h_{ci}^s) = \frac{h_{ci}^s V_p^{s+1} + b V_d^{s+1} - c(h_{ci}^s)}{r+b+h_{ci}^s} \tag{6.19}$$

$$V_{di}^s(h_{di}^s, h_{dj}^s) = \frac{h_{di}^s V_p^{s+1} + h_{dj}^s V_d^{s+1} - c(h_{dj}^s)}{r + h_{di}^s + h_{dj}^s} \tag{6.20}$$

Rearranging terms in (6.18), (6.19) and (6.20) yields the Bellman equations (6.1), (6.2) and (6.3) respectively.

First order condition for the challenger is:

$$\frac{\partial V_{ci}^s}{\partial h_{ci}^s}(h_{ci}^s) = 0 \tag{6.21}$$

[13]Note that when firm i is a challenger, if it does not discover and nature does not adapt between t and $t+dt$, it does not get any profit and has to bear a cost $c(h_{ci}^s)$. If it discovers during the period, it becomes patentee for the next innovation. If nature adapts during the period, it becomes a duopolist in the race for the next innovation. Similarly, when firm i is in a duopoly, if neither it nor its competitor firm j innovates between t and $t+dt$, it has to bear a cost $c(h_{di}^s)$. If it innovates, it becomes the patentee for the next innovation. If its competitor innovates, it becomes the challenger.

Moreover, differentiating (6.19) yields:

$$\begin{aligned}\frac{\partial V_{ci}^s}{\partial h_{ci}^s} &= \frac{V_{pi}^{s+1} - c'(h_{ci}^s)}{r+b+h_{ci}^s} - \frac{h_{ci}^s V_p^{s+1} + bV_d^{s+1} - c(h_{ci}^s)}{(r+b+h_{ci}^s)^2} \\ &= \frac{V_{pi}^{s+1} - V_{ci}^s(h_{ci}^s) - c'(h_{ci}^s)}{r+b+h_{ci}^s}\end{aligned}$$

So (6.21) is equivalent to:

$$c'(h_{ci}^s) = V_{pi}^{s+1} - V_{ci}^s(h_{ci}^s) \tag{6.22}$$

Moreover:

$$\begin{aligned}\frac{\partial^2 V_{ci}^s}{(\partial h_{ci}^s)^2} &= -\frac{\frac{\partial V_{ci}^s}{\partial h_{ci}^s}(h_{ci}^s) + c''(h_{ci}^s)}{r+b+h_{ci}^s} - \frac{V_{pi}^{s+1} - V_{ci}^s(h_{ci}^s) - c'(h_{ci}^s)}{(r+b+h_{ci}^s)^2} \\ &= -\frac{2\frac{\partial V_{ci}^s}{\partial h_{ci}^s}(h_{ci}^s) + c''(h_{ci}^s)}{r+b+h_{ci}^s}\end{aligned}$$

Hence, whatever h_{ci}^s satisfying first order condition (6.21), $V_{ci}^s(h_{ci}^s = -c"(h_{ci}^s)/(r + b + h_{ci}^s) < 0$ and V_{ci}^s is locally strictly concave.

First order condition for duopolist i is:

$$\frac{\partial V_{di}^s}{\partial h_{di}^s}(h_{di}^s, h_{dj}^s) = 0 \tag{6.23}$$

Differentiating (6.20) yields:

$$\begin{aligned}\frac{\partial V_{di}^s}{\partial h_{di}^s} &= \frac{V_{pi}^{s+1} - c'(h_{di}^s)}{r+h_{di}^s+h_{dj}^s} - \frac{h_{di}^s V_{pi}^{s+1} + h_{dj}^s V_{ci}^{s+1} - c(h_{di}^s)}{\left(r+h_{di}^s+h_{dj}^s\right)^2} \\ &= \frac{V_{pi}^{s+1} - V_{di}^s\left(h_{di}^s, h_{dj}^s\right) - c'(h_{di}^s)}{r+h_{di}^s+h_{dj}^s}\end{aligned}$$

So (6.23) is equivalent to:

$$c'(h_{di}^s) = V_{pi}^{s+1} - V_{ci}^s(h_{ci}^s) \tag{6.24}$$

Moreover:

$$\frac{\partial^2 V_{di}^s}{(\partial h_{di}^s)^2} = -\frac{2\frac{\partial V_{di}^s}{\partial h_{di}^s}\left(h_{di}^s, h_{dj}^s\right) + c''(h_{di}^s)}{r+h_{di}^s+h_{dj}^s}$$

Hence, whatever h^s_{di} satisfying first order condition (6.23), $V^s_{di}(h^s_{di}, h^s_{dj}) = -c"(h^s_{di})/(r+h^s_{di} + h^s_{dj}) < 0$ and V^s_{di} is locally strictly concave with respect to its first argument.

It is also useful to note that subtracting (6.24) from (6.24) yields:

$$V^s_{ci} - V^s_{di} = c'(h^s_{di}) - c'(h^s_{ci}) \tag{6.25}$$

Subtracting (6.2) from (6.1) yields:

$$\pi + c(h^s_{ci}) = r(V^s_{pi} - V^s_{ci}) + h^s_{ci}\left(V^{s+1}_{pi} - V^s_{ci}\right) + b\left(V^s_{pi} - V^s_{ci}\right) + h^s_{cj}\left(V^s_{pi} - V^{s+1}_{ci}\right) \tag{6.26}$$

In steady state, substituting (6.24) yields:

$$\pi + c(h_{ci}) = (r + h_{ci} + h_{cj} + b)\, c'(h_{ci}) \tag{6.27}$$

Moreover, subtracting (6.3) from (6.1) yields:

$$\begin{aligned} \pi + c(h^s_{di}) \quad = \quad & r\left(V^s_{pi} - V^s_{di}\right) + h^s_{di}\left(V^{s+1}_{pi} - V^s_{di}\right) + h^s_{dj}\left(V^{s+1}_{ci} - V^s_{di}\right) \\ & + h^s_{cj}\left(V^s_{pi} - V^{s+1}_{ci}\right) + b\left(V^s_{pi} - V^{s+1}_{di}\right) \end{aligned}$$

In steady state, substituting (6.24), (6.24) and (6.25) yields:

$$\pi + c(h_{di}) = (r + h_{di} + h_{dj} + b)c'(h_{di}) + (h_{cj} - h_{dj})\, c'(h_{ci}) \tag{6.28}$$

We look for symmetrical equilibrium, so (6.27) and (6.28) become respectively:

$$\pi + c(h_c) \quad = \quad (r + 2h_c + b)\, c'(h_c) \tag{6.29}$$

$$\pi + c(h_d) \quad = \quad (r + 2h_d + b)c'(h_d) + (h_c - h_d)\, c'(h_c) \tag{6.30}$$

It is interesting to note that if h_c satisfies (6.29), then $h_d = h_c$ satisfies (6.30).

Substituting $c(x) = cx^2/2$, then (6.29) and (6.30) can be written, respectively:

$$3c\,(h_c)^2 + 2(b + r)ch_c - 2\pi \quad = \quad 0 \tag{6.31}$$

$$3c\,(h_d)^2 + 2(b + r)ch_d - 2\pi + 2c(h_c - h_d)d_c \quad = \quad 0 \tag{6.32}$$

(6.31) is equivalent to $P(h_c) = 0$ with $P(x) = 3cx^2 + 2(r+b)cx - 2\pi$. P has two roots:

$$\tilde{h_c} = \frac{\sqrt{(r+b)^2c^2 + 6c\pi} - (r+b)c}{3c} > 0$$
$$\hat{h_c} = -\frac{\sqrt{(r+b)^2c^2 + 6c\pi} + (r+b)c}{3c} < 0$$

Hence, either $h_c^* = 0$ or $h_c^* = \tilde{h_c}$. Yet, $\partial V_c / \partial h_c(0) = [V_p - bV_d/(r+b)]/(r+b) > 0$, because V_p is necessarily superior to V_d (else no duopolist firm would undertake research). So the optimal investment by a challenger cannot be 0, and hence:

$$h_c^* = \frac{\sqrt{(r+b)^2c^2 + 6c\pi} - (r+b)c}{3c}$$

(6.32) is equivalent to:

$$P(h_d) = 2ch_c(h_d - h_c)$$

In equilibrium, $h_c = h_c^* = \tilde{h_c}$. Hence

$$P(h_d) = 2c\tilde{h_c}(h_d - \tilde{h_c})$$

which is equivalent to

$$3c\left(h_d - \tilde{h_c}\right)\left(h_d - \hat{h_c}\right) = 2c\tilde{h_c}(h_d - \tilde{h_c})$$

$\tilde{h_d} = \tilde{h_c}$ is a solution to the previous equation. The other solution $\hat{h_d}$ satisfies thus:

$$3c\left(\hat{h_d} - \hat{h_c}\right) = 2c\tilde{h_c}$$

Hence:

$$\hat{h_d} = \frac{2}{3}\tilde{h_c} + \hat{h_c} = -\frac{2(r+b) + \tilde{h_c}}{3} < 0$$

Thus, once again, either $h_d^* = 0$ or $h_d^* = \tilde{h_c}$. Yet, $\partial V_d / \partial h_{di}(0,0) = V_p/r > 0$. Hence, the optimal investment by a duopolist is the same as the optimal investment by a challenger:

$$h_d^* = \frac{\sqrt{(r+b)^2c^2 + 6c\pi} - (r+b)c}{3c}$$

Moreover, from (6.1), (6.24) and (6.24):

$$V_p = \frac{\pi - c\,(h_c^*)^2 - bch_d^*}{r} = \frac{3\pi + (b-2r)\left[(r+b)c - \sqrt{(r+b)^2c^2 + 6c\pi}\right]}{9r}$$

From (6.24):

$$V_c = V_p - ch_c^* = \frac{3\pi + (r+b)\left[(r+b)c - \sqrt{(r+b)^2c^2 + 6c\pi}\right]}{9r}$$

Finally, from (6.25), as $h_c^* = h_d^*$, $V_d = V_d$, so:

$$V_d = \frac{3\pi + (r+b)\left[(r+b)c - \sqrt{(r+b)^2c^2 + 6c\pi}\right]}{9r}$$

We have supposed so far that the firms actually take part in the patent race. This happens only if $V_c \geq 0$, which is equivalent to $\pi \geq (r+b)^2/2$.[14]

Social planner

Using the same reasoning that enabled to derive V_{pi}^s in the previous appendix subsection, we derive the following expression for $\mathcal{V}_{pc}^s$ (the only difference is that the flow of social profit, w, is not constant as was π because of nature weak adaptation, so the equivalent of π is $\mathbb{E}_t(w)$, expected at time t):

$$\mathcal{V}_p^s \;=\; \int_0^{+\infty} \left[\mathbb{E}_t(w) + \eta_p^s \mathcal{V}_p^{s+1} + b\mathcal{V}_d^{s+1} - c(h_p^s)\right] e^{-(r+b+\eta_p^s)t} dt$$

Defining $N_n(t)$ as the event "nature has weakly adapted exactly n times before t", and $w_n = \omega/\alpha^n$, the flow of social welfare at instant t if nature has weakly adapted

[14]Of course, if $V_c \geq 0$, $V_p \geq 0$. Indeed, $(r+b)c - \sqrt{(r+b)^2c^2 + 6c\pi} \leq 0$ and $r+b \geq b-2r$. Then:

$$(r+b)\left[(r+b)c - \sqrt{(r+b)^2c^2 + 6c\pi}\right] \;\leq\; (b-2r)\left[(r+b)c - \sqrt{(r+b)^2c^2 + 6c\pi}\right]$$

which yields

$$V_c \;\leq\; V_p$$

If $V_c \geq 0$, then $V_p \geq 0$.

n times before t, we get that $\mathbb{E}_t(w) = \sum_{n=0}^{+\infty} N_n(t) w_n$. Moreover, it is a standard result of Poisson processes theory that:

$$N_n(t) = \frac{(\gamma t)^n e^{-\gamma t}}{n!}$$

Hence:

$$\mathcal{V}_p^s = \int_0^{+\infty} \left[\sum_{n=0}^{+\infty} \frac{(\gamma t)^n e^{-\gamma t}}{n!} \frac{\omega}{\alpha^n} + \eta_p^s \mathcal{V}_p^{s+1} + b\mathcal{V}_d^{s+1} - c(\eta_p^s) \right] e^{-(r+b+\eta_p^s)t} dt$$

Using $\sum_{n=0}^{+\infty} (\gamma t)^n / n! = e^{\gamma t}$, $\sum_{n=0}^{+\infty} [(\gamma t)^n e^{-\gamma t}/n!]\, \omega = \omega$:

$$\begin{aligned}
\mathcal{V}_p^s &= \int_0^{+\infty} \left[\sum_{n=0}^{+\infty} \frac{(\gamma t)^n}{n!} \frac{\omega}{\alpha^n} \right] e^{-(r+\gamma+b+\eta_p^s)t} dt \\
&\quad + \int_0^{+\infty} \left[\eta_p^s \mathcal{V}_p^{s+1} + b\mathcal{V}_d^{s+1} - c(\eta_p^s) \right] e^{-(r+b+\eta_p^s)t} dt \\
&= \sum_{n=0}^{+\infty} \left[\int_0^{+\infty} \frac{(\gamma t)^n}{n!} \frac{\omega}{\alpha^n} e^{-(r+\gamma+b+\eta_p^s)t} dt \right] \\
&\quad + \int_0^{+\infty} \left[\eta_p^s \mathcal{V}_p^{s+1} + b\mathcal{V}_d^{s+1} - c(\eta_p^s) \right] e^{-(r+b+\eta_p^s)t} dt
\end{aligned}$$

Define:

$$U_n = \int_0^{+\infty} \frac{(\gamma t)^n}{n!} \frac{\omega}{\alpha^n} e^{-(r+\gamma+b+\eta_p^s)t} dt$$

Integrating by parts:

$$\begin{aligned}
U_n &= \left[\frac{(\gamma t)^n}{n!} \frac{\omega}{\alpha^n} \frac{e^{-(r+\gamma+b+\eta_p^s)t}}{r+\gamma+b+\eta_p^s} \right]_{+\infty}^{0} + \int_0^{+\infty} \frac{n\gamma(\gamma t)^{n-1}}{n!} \frac{\omega}{\alpha^n} \frac{e^{-(r+\gamma+b+\eta_p^s)t}}{r+\gamma+b+\eta_p^s} dt \\
&= \int_0^{+\infty} \frac{\gamma(\gamma t)^{n-1}}{(n-1)!} \frac{\omega}{\alpha^n} \frac{e^{-(r+\gamma+b+\eta_p^s)t}}{r+\gamma+b+\eta_p^s} dt \\
&= \frac{\gamma}{\alpha(r+\gamma+b+\eta_p^s)} \int_0^{+\infty} \frac{(\gamma t)^{n-1}}{(n-1)!} \frac{\omega}{\alpha^{n-1}} e^{-(r+\gamma+b+\eta_p^s)t} dt \\
&= \frac{\gamma}{\alpha(r+\gamma+b+\eta_p^s)} U_{n-1} = \left(\frac{\gamma}{\alpha(r+\gamma+b+\eta_p^s)} \right)^n U_0 \\
&= \frac{\omega}{r+\gamma+b+\eta_p^s} \left(\frac{\gamma}{\alpha(r+\gamma+b+\eta_p^s)} \right)^n
\end{aligned}$$

Hence:

$$\begin{aligned}
\mathcal{V}_p^s &= \frac{\omega}{r+\gamma+b+\eta_p^s}\sum_{n=0}^{+\infty}\left(\frac{\gamma}{\alpha(r+\gamma+b+\eta_p^s)}\right)^n + \frac{\eta_p^s\mathcal{V}_p^{s+1}+b\mathcal{V}_d^{s+1}-c(\eta_p^s)}{r+b+\eta_p^s} \\
&= \frac{\omega}{r+\gamma+b+\eta_p^s}\frac{\alpha(r+\gamma+b+\eta_p^s)}{\alpha(r+\gamma+b+\eta_p^s)-\gamma} + \frac{\eta_p^s\mathcal{V}_p^{s+1}+b\mathcal{V}_d^{s+1}-c(\eta_p^s)}{r+b+\eta_p^s} \\
&= \frac{\omega}{r+\gamma\left(1-\frac{1}{\alpha}\right)+b+\eta_p^s} + \frac{\eta_p^s\mathcal{V}_p^{s+1}+b\mathcal{V}_d^{s+1}-c(\eta_p^s)}{r+b+\eta_p^s} \\
&= \frac{\omega}{r+\beta+b+\eta_p^s} + \frac{\eta_p^s\mathcal{V}_p^{s+1}+b\mathcal{V}_d^{s+1}-c(\eta_p^s)}{r+b+\eta_p^s}
\end{aligned}$$

The equation for $\mathcal{V}_d^s$ is derived as in the duopoly section.

First order conditions can then be written:

$$\begin{aligned}
\frac{\partial\mathcal{V}_p^s}{\partial\eta_p^s} = \frac{-\omega}{(r+b+\beta+\eta_p^s)^2} + \frac{\mathcal{V}_p^{s+1}-c'(\eta_p^s)}{r+b+\eta_p^s} - \frac{\eta_p^s\mathcal{V}_p^{s+1}+b\mathcal{V}_d^{s+1}-c(\eta_p^s)}{(r+b+\eta_p^s)^2} &= 0 \\
\frac{\beta\omega}{(r+b+\eta_p^s)(r+b+\beta+\eta_p^s)^2} + \frac{\mathcal{V}_p^{s+1}-\mathcal{V}_p^s-c'(\eta_p^s)}{r+b+\eta_p^s} &= 0
\end{aligned}$$

$$\begin{aligned}
\frac{\partial\mathcal{V}_d^s}{\partial\eta_d^s} = \frac{\mathcal{V}_p^{s+1}-c'\left(\frac{\eta_d^s}{2}\right)}{r+\eta_p^s} - \frac{\eta_d\mathcal{V}_p^{s+1}-\left[2c\left(\frac{\eta_d^s}{2}\right)+\theta\right]}{\left(r+\eta_p^s\right)^2} &= 0 \\
\frac{\mathcal{V}_p^{s+1}-\mathcal{V}_d^s-c'\left(\frac{\eta_d^s}{2}\right)}{r+\eta_p^s} &= 0
\end{aligned}$$

Which is equivalent to:

$$c'(\eta_p^s) = \mathcal{V}_p^{s+1} - \mathcal{V}_p^s + \frac{\beta\omega}{(r+b+\beta+\eta_p^s)^2} \tag{6.33}$$

$$c'\left(\frac{\eta_d^s}{2}\right) = \mathcal{V}_p^{s+1} - \mathcal{V}_d^s \tag{6.34}$$

First, look for socially optimal R&D effort η_p^*. Then in steady state, (6.33) yields:

$$(\eta_p)^2\,c'(\eta_p) + 2(r+b+\beta)\eta_p c'(\eta_p) + (r+b+\beta)^2 c'(\eta_p) - \beta\omega = 0$$

which, with $c(x) = x^2/2$, is equivalent to $\Phi(\eta_p, \beta) = 0$, where

$$\Phi(x, y) = x^3 + 2(r + b + y)x^2 + (r + b + y)^2 x - \frac{y\omega}{c} \tag{6.35}$$

For any given $\beta \geq 0$, $\Phi(x, \beta)$ admits a single real root in x, η_p^*, which is positive, with:

$$\eta_p^* = \frac{(r + b + \beta)^2}{3\rho} + \frac{1}{3}\rho - \frac{2}{3}(r + b + \beta)$$

where $\rho = \left((r + b + \beta)^3 + \frac{27\omega}{2c}\beta + \frac{3\sqrt{3}}{2}\sqrt{(\omega/c)\beta\left(4(r + b + \beta)^3 + 27(\omega/c)\beta\right)}\right)^{1/3}$. Since $\partial\mathcal{V}_p/\partial\eta_p(0) = \beta\omega/[(r + b)(r + b + \beta)] > 0$, we may rule out corner solution $\eta_p = 0$, and the socially optimal investment in R&D is η_p^* indeed.

Now, we look for the socially optimal level of research after nature has strongly adapted, η_d^*. We restrict our study to the case where nature does not weakly adapt, *i.e.* $\beta = 0$. Rearranging (6.11) and (6.10) yields:

$$\begin{aligned} r\mathcal{V}_p^s(\eta_p^s) &= \omega + \eta_p^s\left(\mathcal{V}_p^{s+1} - \mathcal{V}_p^s\right) + b\left(\mathcal{V}_d^{s+1} - \mathcal{V}_p^s\right) - c(\eta_p^s) && (6.36) \\ r\mathcal{V}_d^s(\eta_d^s) &= \eta_d^s\left(\mathcal{V}_p^{s+1} - \mathcal{V}_d^s\right) - \left[2c\left(\frac{\eta_d^s}{2}\right) + \theta\right] && (6.37) \end{aligned}$$

Subtracting (6.37) from (6.36) and rearranging terms yields, in steady state:

$$r\left(\mathcal{V}_p - \mathcal{V}_d\right) = \omega + b\left(\mathcal{V}_d - \mathcal{V}_p\right) - c(\eta_p) - \eta_d\left(\mathcal{V}_p - \mathcal{V}_d\right) + \left[2c\left(\frac{\eta_d}{2}\right) + \theta\right] \tag{6.38}$$

In steady state, if $\beta = 0$, then $\eta_p = 0$. Hence:

$$(r + b + \eta_d)\left(\mathcal{V}_p - \mathcal{V}_d\right) = \omega + \theta + 2c\left(\frac{\eta_d}{2}\right) \tag{6.39}$$

Substituting (6.33), we get:

$$\left(\frac{\eta_d}{2}\right)^2 + (r + b)\frac{\eta_d}{2} - \frac{\omega + \theta}{c} = 0 \tag{6.40}$$

A similar reasoning to the one developed previously allows to dismiss any corner solution, and the socially optimal investment in R&D after nature has strongly adapted is:

$$\eta_d^* = \frac{\sqrt{(r + b)^2c^2 + 4c(\omega + \theta)} - (r + b)c}{c} \tag{6.41}$$

Monopolist firm

Suppose a monopolist firm is operating. We still assume that it does not invest in R&D while it is patentee, and only invests after nature has adapted. If we denote H^s its effort to discover the s^{th} innovation, then the set of Bellman equations (6.1) and (6.3) become:

$$\begin{aligned} r\mathcal{V}_p^s &= \pi + b\left(\mathcal{V}_d^{s+1} - \mathcal{V}_p^s\right) &(6.42)\\ r\mathcal{V}_d^s(H) &= H^s\left(\mathcal{V}_p^{s+1} - \mathcal{V}_d^s\right) - c(H^s) &(6.43)\end{aligned}$$

The first order condition associated with maximizing (6.43) is

$$c'(H^s) = \mathcal{V}_p^{s+1} - \mathcal{V}_d^s \tag{6.44}$$

As in the previous sections, in steady state we obtain the following equation for H:

$$H^2 + 2(r+b)H - \frac{2\pi}{c} = 0 \tag{6.45}$$

A similar reasoning similar to the one developed in the first section of the paper allows to dismiss corner solutions, and the optimal monopolist's investment is:

$$H^* = \frac{\sqrt{(r+b)^2c^2 + 2c\pi} - (r+b)c}{c} \tag{6.46}$$

Proofs of propositions

Proof of proposition 1: Denoting $h = h_c^* = h_d^*$, we get:

$$\frac{\partial h}{\partial \pi} = \frac{1}{\sqrt{(r+b)^2c^2 + 6c\pi}} > 0$$

$$\frac{\partial h}{\partial b} = \frac{1}{3}\left[\frac{c(r+b)}{\sqrt{(r+b)^2c^2 + 6c\pi}} - 1\right] < 0$$

Q. E. D.

Proof of proposition 2: Consider first the case where $\beta = 0$, which represents the case in which nature does not weakly adapt, and only adapts strongly. Then $\rho = r + b$ and $\eta_p^* = 0$.

Reciprocally, consider the limit case where $\beta \to +\infty$, which represent the case in which nature adapts very fast, reducing immediately after innovation social surplus to 0. Then, $\rho \approx (r + b + \beta)$ and, hence, $\eta_p^* \to 0$.

Applying implicit function theorem to the definition of η_p^*, $\Phi(\eta_p^*, \beta) = 0$:

$$\frac{\partial \eta_p^*}{\partial \beta} = -\frac{\frac{\partial \phi}{\partial \beta}(\beta, \eta_p^*)}{\frac{\partial \phi}{\partial x}(\beta, \eta_p^*)} = \frac{\left[\left(\eta_p^*\right)^2 + 2(r+b)\eta_p^* + (r+b+\beta)(r+b-\beta)\right]\eta_p^*}{\left[3\left(\eta_p^*\right)^2 + 4(r+b+\beta)\eta_p^* + (r+b+\beta)\right]\beta}$$

which is signed as $\left(\eta_p^*\right)^2 + 2(r+b)\eta_p^* + (r+b+\beta)(r+b-\beta)$. For low values of β (in particular $\beta < r + b$), $\partial \eta_p^*/\partial \beta > 0$. Hence, there exists a threshold $\bar{\beta} > r + b$ so that $\partial \eta_p^*/\partial \beta > 0$ for all $\beta \geq \bar{\beta}$.

Moreover, η_p^* is a continuous function of β, defined on a set S so that $\mathbb{R}^+ \subset S$. As $\eta_p^*|_{\beta=0} = 0$ and $\lim_{\beta \to +\infty} \eta_p^* = 0$, then η_p^* is bounded by an upper boundary η_p^{sup}. Hence, whatever β,

$$\left(\eta_p^*\right)^2 + 2(r+b)\eta_p^* + (r+b+\beta)(r+b-\beta) \leq \left(\eta_p^{sup}\right)^2 + 2(r+b)\eta_p^{sup} + (r+b+\beta)(r+b-\beta)$$

Yet:

$$\lim_{\beta \to +\infty} \left[\left(\eta_p^{sup}\right)^2 + 2(r+b)\eta_p^{sup} + (r+b+\beta)(r+b-\beta)\right] = -\infty$$

Hence there exists $\hat{\beta}$ so that whatever $\beta \geq \hat{\beta}$, $\partial \eta_p^*/\partial \beta < 0$.

Q. E. D.

Proof of proposition 3: We aim to compare η_p^* and h_c^*. In order to do so, we sign $\Phi(h_c^*, \beta)$. Indeed, as $\Phi(x, \beta)$ is increasing in x for all β, $\eta_p^* > h_c^*$ if and only if $\Phi(h_c^*) < 0$. Yet:

$$\Phi(h_c^*, \beta) = h_c^*\beta^2 + 2\left[(h_c^*)^2 + (r+b)h_c^* - \frac{\omega}{2c}\right]\beta + (h_c^*)^3 + 2(r+b)\left(h_c^*\right)^2 + (r+b)^2 h_c^*$$

For any given h_c^*, $\Phi(h_c^*, y)$ is a second degree polynomial in y. Its reduced discriminant is:

$$\begin{aligned}\delta &= \left[(h_c^*)^2 + (r+b)h_c^* - \frac{\omega}{2c}\right]^2 - h_c^*\left[(h_c^*)^3 + 2(r+b)\left(h_c^*\right)^2 + (r+b)^2 h_c^*\right] \\ &= \frac{\omega}{c}\left[\frac{\omega}{4c} - \left[(h_c^*)^2 + (r+b)h_c^*\right]\right]\end{aligned}$$

Yet, since h_c^* is a root of P, $(r+b)h_c^* + (h_c^*)^2 = \pi/c - (h_c^*)^2/2$. Hence:

$$\begin{aligned}\delta &= \frac{\omega}{c}\left[\frac{\omega}{4c} - \left[\frac{\pi}{c} - \frac{(h_c^*)^2}{2}\right]\right] \\ &= \frac{\omega}{c^2}\left[\frac{\omega}{4} - \frac{6\pi + (r+b)\sqrt{(r+b)^2c^2 + 6c\pi}}{9}\right]\end{aligned}$$

$\Phi(h_c^*, y)$ thus has real roots in y if and only if $\omega/(4c) - [(h_c^*)^2 + (r+b)h_c^*]$ is positive. In addition, in that case, these roots are necessarily positive.[15] Denoting β_1 and β_2 these roots, if $\beta \in [\beta_1, \beta_2]$, then private duopoly overinvests in R&D.

Q. E. D.

Proof of proposition 4: The first part of the proposition can be obtained by simply differentiating (6.14) with respect to ω and θ. For the remainder, the relevant values to be compared are $\eta_d^*/2$ and h_d^* (as we have defined η_d as the total social planner R&D effort after nature has strongly adapted, while h_d^* is the individual R&D effort of each firm in the duopoly). Then:

$$\frac{\eta_d^*}{2} - h_d^* = \frac{\sqrt{(r+b)^2c^2 + 4c(\omega+\theta)} - (r+b)c}{2c} - \frac{\sqrt{(r+b)^2c^2 + 6c\pi} - (r+b)c}{3c}$$

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[15] If $\omega/(4c) - [(h_c^*)^2 + (r+b)h_c^*] \geq 0$, then:

$$(h_c^*)^2 + (r+b)h_c^* - \frac{\omega}{2c} \leq (h_c^*)^2 + (r+b)h_c^* - \frac{\omega}{4c} \leq 0$$

Thus:

$$\frac{\partial\Phi}{\partial y}(h_c^*, 0) = 2\left[(h_c^*)^2 + (r+b)h_c^* - \frac{\omega}{2c}\right] \leq 0$$

Hence, when $\omega/(4c) - [(h_c^*)^2 + (r+b)h_c^*]$, $\Phi(h_c^*, y)$ is a second degree polynomial in y that admits two real roots and which derivative in 0 is negative. Its roots are thus both positive.

It is easy to prove that whatever $\omega > \pi$, $\theta > 0$, $\eta_d^*/2$ is superior to h_d^*. Indeed,

$$\frac{\eta_d^*}{2} - h_d^* = \frac{3\sqrt{(r+b)^2c^2 + 4c(\omega+\theta)} - 2\sqrt{(r+b)^2c^2 + 6c\pi} - (r+b)c}{6c}$$

This difference is obviously increasing in both ω and θ. Hence, if it is positive for their minimum values (namely $\omega = \pi$ and $\theta = 0$), it is true for any value. Define $f(x,y)$ as:

$$f(x,y) = \frac{3\sqrt{x^2+4y} - 2\sqrt{x^2+6y} - x}{6}$$

For any $x \in \mathbb{R}^+$,

$$\frac{\partial f}{\partial y} = \frac{1}{\sqrt{x^2+4y}} - \frac{1}{\sqrt{x^2+6y}} \geq 0, \quad \forall y \geq 0$$

So whatever $\pi \in \mathbb{R}^+$, for $\omega = \pi$ and $\theta = 0$, $\eta_d^*/2 - h_d^* \geq 0$. Finally, whatever $\omega \geq 0$ and $\theta \geq 0$, $\eta_d^*/2 \geq h_d^*$.

Q. E. D.

Proof of proposition 5: Assume $\beta = 0$. It is easy to show that $2h_d^* \geq H^* \geq h_d^*$. Indeed:

$$H^* - h_d^* = \frac{3\sqrt{(r+b)^2c^2 + 2c\pi} - \sqrt{(r+b)^2c^2 + 6c\pi} - 2(r+b)c}{3c}$$

Define $g(x,y) = 3\sqrt{x^2+y} - \sqrt{x^2+3y} - 2x$. For all $x \in \mathbb{R}^+$, $g(x,0) = 0$, and $g_y = 3/\sqrt{x^2+y} - 3/\sqrt{x^2+3y}$, which is positive for all x, y positive. Hence, $g(x,y) \geq 0$ for all $x \geq 0, y \geq 0$. In particular, $H^* - h_d^* \geq 0$.

$$H^* - 2h_d^* = \frac{3\sqrt{(r+b)^2c^2 + 2c\pi} - 2\sqrt{(r+b)^2c^2 + 6c\pi} - (r+b)c}{3c}$$

The same reasoning shows that $H^* \geq 2h_d^*$.

The relative magnitudes of H^* and $\eta_d^*/2$, in turn, depend more on the parameters:

$$H^* - \frac{\eta_d^*}{2} = \frac{2\sqrt{(r+b)^2c^2 + 2c\pi} - \sqrt{(r+b)^2c^2 + 4c(\omega+\theta)} - (r+b)c}{2c}$$

Hence,

$$\frac{\eta_d^*}{2} \geq H^* \;\; \Leftrightarrow \;\; (r+b)^2 c + 2\pi - (r+b)\sqrt{(r+b)^2c^2 + 2c\pi} \leq \omega + \theta \qquad (6.47)$$

The inequality is always verified for large values of ω and θ (*i.e.* ω significantly larger than π and θ sufficiently larger than 0).
Finally, we look for conditions under which the duopolist's effort is closer to social optimum than the monopolist's one.
We have shown that $H^* \geq h_d^*$. Hence, a necessary condition (not sufficient) for the monopoly to be less desirable than the duopoly is that $H^* \geq \eta_d^*/2$ (otherwise, $\eta_d^*/2 \geq H^* \geq h_d^*$ and H^* is always closer to $\eta_d^*/2$ than h_d^*). Moreover, when this condition is met, H^* is all the further from $\eta_d^*/2$ that the LHS in (6.47) is small. Finally, the further H^* from η_d^* while $H^* \geq \eta_d^*/2$, the more likely it is that the duopoly will be more socially desirable than the monopoly. Denote:

$$f(c,\pi) = (r+b)^2 c + 2\pi - (r+b)\sqrt{(r+b)^2c^2 + 2c\pi}$$

It is easy to show that $\partial f/\partial c \leq 0$ and $\partial f/\partial \pi \geq 0$. Hence, for given values of π, ω and θ, high values of c make condition (6.47) more likely to be verified. High values of c thus make the monopoly more likely to drive a higher social surplus than the duopoly.

Q. E. D.

General conclusion

Research and development on varieties has been, and will remain, a major determinant of the way agricultural commodities are produced, of the quantity of output achieved by farmers, and on the consequences of production beyond the farmers and consumers. It will probably take a large part in the completion of the objective to tackle hunger in the coming fifty years. In this endeavor, public policies will have to play a major role, providing direct support and, more importantly, the necessary institutional framework for research performed by the private sector. In the design of such policies, environmental consequences of crops innovations, *per se*, appear not to have been taken into account yet. In a context of growing environmental concern, in particular with respect to the footprint of agriculture, it should be so in the future.

1 Main results

In the first part of this dissertation, we have focused on innovation *per se*. We have shown, in particular, that "crops innovation" is neither an integrated nor uniform reality. On the contrary, it is very diverse, and the environmental externalities of a new variety may not be similar to those of another. Moreover, the environmental impact of crops innovation has multiple facets, and is still debated. In order to conclude whether more or less research is needed, it is necessary to define an objective function for policymakers, in which the different aspects of the environment that are impacted by crops innovations are weighted accordingly to social preferences. It seems however that for most objective functions, the environmental impact of the major types of innovation on varieties has been positive, overall. We developed a model to focus on a particular aspect of environmental externality of innovation.

We studied the consequences on biodiversity conservation, in the framework of the land sharing/land sparing debate, of the different types of innovation on varieties. The type of innovation, the shape of demand, and the substitutability of production factors are essential drivers of the land sparing and/or land sharing effect of innovation.

In the second part, we have focused on the institutional framework applicable to innovation on varieties. The regime of intellectual property protection applicable to plant varieties has evolved significantly in the last 40 years. Whether a specific regime for plants will remain in force is questioned by the recent evolution, and the consequences of such changes are still uncertain. We also reviewed the social value of such innovation, and the literature showed that R&D on varieties has be socially very profitable for the last fifty years, at least.

In the third part, we have studied the process of research and development, and the way it is conducted among firms. We reviewed the existing analytical framework of research and development, and innovation on varieties. The existing literature showed that perfect competition in R&D is not always desirable. We reviewed various papers in the theoretical literature that suggested some improvements of intellectual property protection systems, that could be socially beneficial under rather weak conditions: first user defense, follow-up clauses, etc. We also highlighted the lack of account for environmental impacts of this R&D in existing literature. Innovation on plant varieties is quite a specific one, because newly developed generations get obsolete faster due to adaptation on pests. Such feature of crops may justify the coexistence of different regime of intellectual property protection. We developed a model that aimed at determining whether a duopoly or a monopoly may conduct a socially optimal level of research, in a context of nature adaptation and with environmental externalities of innovation. We found a crucial role for the speed of pests adaptation. If and only if nature adapts very slowly or very fast, the private sector overinvests in R&D. This suggests that incentives for research, and thus the conditions of intellectual property protection, should be tailored to the speed of adaptation of nature.

2 Limitations

Some of the limitations of the literature we reviewed and, further, of the models we developed, have been highlighted in the corresponding parts of this dissertation. However, some general limitations of our approach may be summarized here.

A first limitation of this work is to build on an imperfect comprehension of the mechanisms at stake in the environmental impact of innovation on crops. In the first chapter of this dissertation, we underlined the fact that the actual environmental externalities of agricultural R&D are still much debated. In our first paper, this obliged us to restrict to a general form for this phenomenon, without being able to specify it further that what we have done. In the second paper, we had to refrain from going a step further by valuing the impacts of the different types of innovation on biodiversity conservation. Indeed, the benefits of land sharing and land sparing on animal species are still under research in ecology. This allowed us to study only the direction of the innovation consequences, but did not allow to discuss whether a direction is more desirable than another.

We have also implicitly assumed that future innovation will have roughly the same characteristics as previous innovation, that it will merely take improvements of varieties a step further in the same direction. Hence, our reflexion may not account properly for future technological breakthroughs (as has been the introduction of biotechnologies in agricultural research). This has been a flaw for both models we built. In our first model, we supposed that innovation only restores initial productivity of agricultural production. As exemplified in the first part of the thesis, the development of new varieties (in particular GM ones) has gone much further than this, and increased considerably the productivity of crops. In our second model, we have examined the consequences of improving further existing GM varieties, but did not account for innovations that would, for instance, require new inputs to be introduced in the production process.

More generally, we have chosen to look for analytical solutions, which implied several simplifications and particular specifications in the models we developed. Obtaining analytical solutions is very useful to get the intuitions behind the mechanisms at stake, which justifies our choices, probably more than numerical resolution in our specific case.[16] However, the simplification assumptions we made may hide some

[16] In particular, numerical simulations would have used uncertain valuations of externalities.

important issues that we may not be aware of. We have tried to discuss them as much as possible, and to suggest how they influence results, but we may have not properly done so for some of them.

Finally, our works are based on a theoretical analysis that is not supported enough by data analyses. Empirical validation would strengthen their conclusions.

3 Perspectives

The main objective of this dissertation was to extend the studies of environmental externalities of agricultural production to one of the major determinants of the evolution of its practices, namely research and development. We believe the impact of innovation on the environment should be accounted for, in particularly when designing the policies setting the institutional framework for R&D activities. Further work, however, will be needed to, first, understand better the mechanisms at stake, and, second, shed a more complete light on policy decisions.

A further field of investigation is an empirical evaluation of the consequences of innovation on land use, as suggested by Hertel (2012), and on biodiversity, as we complemented with chapter 2. Villoria et al. (2014) showed that the empirical treatment of the consequences of agricultural innovation on input use is still rather scarce, and the existing empirical studies do not allow to clearly confirm or reject the results of our theoretical analysis. The discussion we provide advocates for an evaluation that takes different types of innovation into account, which will make empirical results more significant.

Another direction for future investigation is on the environmental consequences of the R&D process. First, the direction and magnitude of the already identified impacts are still vividly debated, in particular because of lack of proper empirical analyses. More work is needed to reach a more stable vision on these questions. Second, other sources of externalities for R&D on varieties may exist, that have not been acknowledged as such by the literature. Once these effects are better understood and quantified, one may valuate innovation more accurately, accounting for its environmental value and cost. This would bring a significant improvement to the empirical works based on the models of Griliches (1958), Moschini and Lapan (1997) or Lence et al. (2005). This would also refine the conclusions of chapter 6.

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