Building the Knowledge Stock:

Lags, Depreciation and Uncertainty in Agricultural R&D

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Abstract

The search for an appropriate methodology to analyse the relation between R&D investments and the knowledge stock is the main purpose of the paper. The high estimates of internal rates of return on agricultural R&D reported in the literature suggest that there are major empirical problems with the traditional attribution of productivity growth to R&D investments. We model a stochastic gestation lag of research investment and a geometric depreciation of the knowledge stock. This model of knowledge accumulation from R&D investments outlines the basic parameters underlying the investment lag structure. According to the different types of research project, the approach is applied to public R&D expenditure in Italian agriculture in order to ascertain the empirical consequences and potential of the model.

1. Introduction

In the past fifteen years increasing effort has been devoted to measuring the internal rate of return in agricultural R&D. This strand of literature has now become so vast to stimulate comprehensive analyses of the state of the art. In a recent survey, which includes 1772 estimates covering every kind of agricultural research as well as investments in extension, Alston *et al*. (2000) come about with an average rate of return of 81% and a standard deviation of 216%. These astonishing figures suggest that very high and seemingly unreliable returns are coupled with a pronounced volatility even when data refer to the same country and period (Alston and Pardey, 2000).

Looking at these estimates, one gets the feeling that most of these studies suffer from common methodological problems. Two facts strengthen such an opinion. Firstly, analogous results prevail in other sectors, hence under different contexts, with studies using the same methodology (Hall, 1996; Griliches, 1998). Secondly, high returns mainly refer to public agricultural R&D, which is commonly interpreted as an incentive towards increasing investments. On the contrary, in the past decade many developed and/or developing countries have reduced their public research effort in real terms (Alston *et al*., 1998; Huffman e Just, 1999). The Italian case does not make an exception in this respect.

The main issue concerning the measurement of R&D returns has to do with the so-called *attribution problem* (Alston and Pardey, 2000). Since the return is computed by comparing the flow of benefits and costs associated with a given investment, a difficulty arises in correctly attributing the benefits to the cost that really generated them. This attribution requires to specify how the investment distributes its effects over time; that is, one must identify the lag structure of the R&D effects.

In this study, the attribution problem is mainly analysed from a methodological point of view. In particular, our purpose is to define those parameters that are relevant for the accumulation of the knowledge stock and depend on the nature of the research programme. These parameters eventually establish the lag structure of the R&D effects, and thus affect the estimates of research returns.

The paper is organised as follows. Section 2 describes the prevailing theoretical framework in the literature and traces the definition of the lag structure back to the problem of the accumulation of a technological asset. Section 3 shows that this stock has some specific properties that render the standard concepts applied to physical capital inappropriate when they are referred to the knowledge stock. An alternative approach is therefore proposed which seeks to identify the fundamental parameters for the quantification of the knowledge stock and its user's cost. Section 4 introduces some empirical implications of the model. Italian agriculture is used as case study; here the knowledge stock is computed according to different hypotheses about the nature of the underlying research programme: basic, applied or development. On the basis of existing estimates of the lag structure of R&D effects, a calibration of the fundamental parameters is also proposed. Section 5 concludes.

2. R&D and productivity: the attribution problem

Most studies on the return on agricultural R&D are based on the neoclassical representation of technology. From the primal, the problem is viewed through a production function:

(1) $$Y = F(L, K, T, t)$$

where *Y*, *L* and *K* are output, labor and physical capital respectively; the trend *t* represents the exogenous technical level, and *T* is the technological stock resulting from the following knowledge function (Jones e Williams, 1998):

(2) $T = G\left(W(B)R\right)$

$W(B)R$ is a linear function in research investment (*R*), and *B* is the backward operator. So, the knowledge stock is a linear combination of past investments. For the sake of simplicity, let the production function[1] (1) be of the Cobb-Douglas type with constant returns of scale on conventional inputs:

(3) $Y = L^{a} K^{1-a} T^{g} e^{l\,t}$

and assume that:

(4) $T = W(B)R$

Substituting, it follows that:

(5) $Y = L^{a} K^{1-a} \left[W(B)R\right]^{g} e^{l\,t}$

It is then possible to compute an index of total factor productivity (*TFP*):

(6) $TFP = \dfrac{Y}{L^{a} K^{1-a}} = \left[W(B)R\right]^{g} e^{l\,t}$

which in terms of growth rates becomes:

(7) $\dfrac{\dot{TFP}}{TFP} = l + g\left[\dfrac{W(\dot{B})R}{W(B)R}\right]$

The expression (7) relates benefits and costs of a given research investment. The benefits are given by the growth of total productivity[2] net of the intercept l indicating the contribution of the exogenous technical change; the costs arise from the R&D expenditure required to generate the growth of the knowledge stock.

Conceptually, the return on R&D depends on two distinct elements: the parameter γ, which measures the contribution of stock T to production, and the distribution $W(B)R$, which controls the accumulation of knowledge stock. The first task, therefore, is the correct specification of (7).[3] Besides, however, the question of the correct calculation of the knowledge stock is still unsolved. It is on this second problem that we shall mainly focus here. In order to show that the building of the stock is in fact a problem of attribution over time[4], let us assume that:

(8) $$W(B)R_t = (w_0+w_1B+w_2B^2+..+w_sB^s+..)R_t = w_0R_t+w_1R_{t-1}+w_2R_{t-2}+..+w_sR_{t-s}+..$$

where t is the current year and s is the investment age. In (8), the stock at time t is the sum of past investments calculated in efficiency units. The weights define how relative efficiency changes with the investment age. If the efficiency of a brand-new investment is maximum ($w_0=1$), a unit of s-year-old capital provides the same services as w_s units of new capital. On this basis, $W(B)R_t$ is an estimate of the aggregate knowledge stock at time t, since it indicates the amount of new capital required to obtain the same level of services as supplied by the old vintage capital still in use (Hulten and Wykoff, 1996).

In applied studies, many different specifications of (8) have been adopted, and the choice among them seems to be guided more by empiricism rather than theory. According to Alston *et al*. (2000), this is the main source of the enormous variability in the estimated returns. In principle, it should be possible to estimate the system of weights by substituting (8) in equation (6) or (7); in fact, this approach is hardly viable. The real impact of research investment[5] is a long lasting phenomenon, consequently the number of lags to be considered is too high with respect to the length of available time series. Therefore, *ad hoc* assumptions are usually introduced. One solution is to assume *ex-ante* the lag distribution and to define the system of weights on the basis of few estimated parameters.[6] Alternatively, the form of the lag structure is left free, but to save degrees of freedom, lags are truncated to an overly short period. Unfortunately, both alternatives produce bias estimates of returns.[7]

Hallam (1990), amongst others, questions this empirical procedure on the grounds of both the lack of formal statistical tests on the form of the lag structure, which in turn may yield inconsistent estimates, and non-stationarity of the involved series. Under non-stationarity, both (5) and (6) can generate spurious regressions (Granger and Newbold, 1981) and cause the unreliable high return on R&D[8], as well. Yet, this sound criticism against the standard approach and in favour of a detailed analysis of the data generating process can not help in terms of identifying the lag structure. Hallam himself admits that, with the current state of the art and considering the short time series available, endeavouring to obtain econometric estimates of the whole weight structure may be too ambitious. Apparently, the method imposing the least *ex-ante* restrictions is the nonparametric approach (Chavas *et al.*, 1997; Esposti, 2000). Such an approach let the shape of the weight distribution free, though an arbitrary truncation its length may still be needed.

As this point is quite controversial (Schimmelpfenning and Thirtle, 1994), one is encouraged to look for other solutions. In fact, defining the real lag structure is mainly a theoretical-methodological problem, rather than an empirical one, since equation (8) involves the inherent mechanism linking R&D investments to the accumulation of the knowledge stock. The question is what lies "behind" the lag structure; what technical and economic characteristics of the investment bring about. Therefore, an alternative approach to econometric estimation relies on recovering the series of weights on the basis of the fundamental parameters that underlie the accumulation of the knowledge stock.[9]

3. From R&D investments to the knowledge stock

In principle, should it be necessary to calculate the productivity effects of a single, specific, well-defined research programme, it may be possible to recover the timing of the events in detail.[10] The task becomes difficult, if not impossible, with aggregate data (say, the whole public agricultural R&D in Italy). A general approach is therefore needed which must take account both the specific nature of the knowledge stock and the inherent uncertainty of research activities.

3.1 The nature of the knowledge stock

In the case of physical capital, it is customary to assume that the stock depends essentially on the investment's depreciation rate since the beginning of its service life.[11] There are two main causes of *decay*. The first is the wear and tear of the capital: machinery, buildings and infrastructure are subject to physical *deterioration*, which makes them increasingly less efficient. The second is technical *obsolescence*, that is, a decreasing level of utilisation. Even when capital does not physically deteriorate, and is therefore still usable, its utilisation may decrease because it becomes less and less useful. This happens because the old investments are displaced by new production methods or by brand-new assets.

To what extent do these considerations apply to the knowledge stock as well? It is not physical in nature, so that the idea of deterioration is hardly tenable. If the research capital were subject to wear and tear, according to equation (5) production itself would cease sooner or later, whenever new R&D investments were lacking. The main idea is that existing knowledge cannot vanish because it is immaterial. It may instead be replaced by more recent and upgraded knowledge. The technological stock may therefore become obsolete and its utilisation decrease whenever new knowledge becomes available: new R&D investments partially substitute old ones. It may also happen that the utilisation of the old knowledge decreases even when new R&D is lacking, due to a change in external conditions; in this case too, the knowledge stock may become obsolete without vanishing.[12]

Equation (8) should be specified so that the R&D effects diminish but potentially last forever. This effect can be obtained by means of the perpetual inventory method (PIM). Under the hypothesis of a constant rate of efficiency decrease, the PIM requires very limited information: an estimate of the initial knowledge stock and the series of R&D gross investments.[13]

The PIM can be written as follows (Park, 1995)[14]:

(9) $T_t = T_{t-1}(1\text{-}d) + R_t$

where d is the decay rate of efficiency. By backward substitution, equation (9) can be expressed as a weighted sum of investments of different ages:

(10) $T_t = R_t + (1\text{-}d)R_{t-1} + (1\text{-}d)^2 R_{t-2} + .. + (1\text{-}d)^s R_{t-s} + .. = w_0 R_t + w_1 R_{t-1} + w_2 R_{t-2} + .. + w_s R_{t-s} + ..$

where $w_s=(1\text{-}d)^s$. If g is the investment growth rate, assumed constant in the long run for simplicity, $(1+g)=R_t/R_{t-1}$, we can rewrite the above PIM model as follows:

(11) $T_t = R_t(1+g)/(g+d)$

which will be positive if both $(1+g)$ and $(g+d)$ are greater than zero. Conditional on a given d, an approximated initial value T_0 can be calculated.

Although the hypothesis of a constant decay rate is often thought of as working assumption, Jovanovic and Nyarko (1998) show that equation (10) can be viewed as a Taylor series linear expansion, i.e. as a linear approximation to the unknown stock. The latter is derived through a theoretical information model of how a firm uses R&D investment to install the desired technology. Accordingly, rather than being a technical parameter to be assumed, the decay rate contains a body of economic information to be made clear.

Firstly, a constant d implies geometric depreciation: that is, a more intense reduction of efficiency during the early part of the investment service life. In general, this hypothesis looks rather implausible if referred to numerous physical assets. Agricultural machinery tends to maintain efficiency at a level very close to that of a brand-new asset in the first years, to decline rapidly towards the end of its service life (Ball *et al*., 1993; Caiumi *et al*, 1995; Annunziato and Ganoulis, 1998). Again, however, the nature of technological stock is peculiar. Most research programmes produce short-lived new knowledge; only a few projects yield discoveries and innovations of enduring impact. Most innovations, in agriculture as well as other activities, are incremental and will presumably soon be replaced, while only few of them are radical and long lasting (de Bresson, 1991). In aggregate terms, this distinctive feature of the technological stock implies a constant d, that is, geometric decay.[15]

Equation (9) has also another interpretation. Recalling that several lagged research expenditures enter equation (2), the stock growth rate depends on both the current expenditure and the existing stock, $\dot{T}_{t+1} = f(R_{t+1}, T_t)$. The derivative of this function with respect to the existing stock has a specific meaning. ¶*f*/¶*T*>0 indicates that higher past investments, now cumulated in T_t, increase the contribution of R_{t+1}. ¶*f*/¶*T*<0, suggests that higher past investments will make the current ones less effective. Both cases are acknowledged as possible and typical behaviour of R&D investments: the former is called *spillover effect*, the latter *fishing-out* or *congestion effect* due to the repetition of efforts and results already produced in the past.[16] Which one is going to prevail depends on the context. However, since $\Delta T_t = R_t - dT_{t-1}$, equation (9) implies a prevalence of the congestion effect: part of the new investment is needed to replace old decaying knowledge, and this part will be greater, in absolute terms, the greater the stock. A constant decay rate not only imposes the form taken by the stock decay over time but it also defines the needed substitution rate; that is, the investment required to maintain the knowledge stock constant.

The logical correspondence between fishing-out effects and increasing maintenance investments has obvious applications in agriculture, e.g., the case of many new varieties with improved resistance against pathogens or wide-range pesticides or herbicides. These varieties progressively lose their advantage as the pathogen develops resistance, which requires new investments to upgrade the genetic make-up of the variety or to introduce new improved varieties. At the same time, however, in order to enable the selection and introduction of new varieties, research investments are required to preserve the original and native germoplasm, which would otherwise be displaced by the growing of the new varieties. An example of these two combined forms of R&D investment is provided by the genetically modified varieties recently introduced in the USA (Barnett and Gibson, 1999).

There is a further implication for the economic analysis of the decay rate d. The rate of substitution, as well as maintenance, of both incremental and radical innovations does not depend solely on their inherent characters; it depends also on how fast new knowledge can be produced. New techniques, qualitatively improved inputs and so on, may accelerate the obsolescence of the existing knowledge: the faster this technological upgrading, the more rapid the decay rate (Jovanovic and Nyarko, 1998). Since this movement across technological grades becomes quicker, the greater the net research effort, the d can be assumed to be only initially constant, because it will then accelerate if the research induces technological upgrading. Therefore, d tends to be endogenous with respect to the underlying research effort.

The speed of technological upgrading is difficult to measure, however. It depends on the introduction of radical changes in techniques and production practices, and therefore on effort mostly devoted to basic research, but it also depends on the exogenous technical change approximated by a trend: both will eventually allow switching to a new level of technology. Thus, the speed of the technological upgrading can be expressed by the general function $[f(t, \sum_t R_t)]$. So, under progressive technological upgrading, the obsolescence of the old stock accelerates and the asset may even go to 0: knowledge can vanish but only if positive net research investments make the obsolescence depend on the speed of technological upgrading. Therefore, we can generally write that:

$$(12) \quad \begin{cases} d_s = d^*\left[1+ f\left(t, \sum_t R_t\right)\right]^{s-G-1}, & \text{if } d^*\left[1+ f\left(t, \sum_t R_t\right)\right]^{s-G-1} < 1 \\ d_s = 1, & \text{if } d^*\left[1+ f\left(t, \sum_t R_t\right)\right]^{s-G-1} \geq 1 \end{cases}$$

$\forall s > G$, where G is the period when the research investment reaches full-efficiency and then begins to become obsolete; this will be explained in detail below. d^* is the initial (at year G) decay rate. According to this argument, the d adopted in empirical studies should not be interpreted as the value assumed for d^* but as the average decay rate over the obsolescence-accelerating service life. The obsolescence acceleration implies d_s increases over s, which always holds under technological upgrading that is $\left[f\left(t, \sum_t R_t\right)\right] > 0$.

3.2. Uncertainty and knowledge stock.

Although equation (9) represents a number of relevant features of the knowledge stock, it can not detect an important aspect of research investment, namely the inherent risk in terms of both timing and outcome. According to its nature (basic, applied or development), a research programme does not immediately and automatically yield technological knowledge. This is because research results, by definition, may be more or less successful and useful. This aspect is particularly relevant when we wish to define *ex-ante* the expected contribution of an R&D investment to the stock, or when we need to build the stock *ex-post* given aggregate data which do not allow detailed reconstruction of the sequence of the research results.

The main source of uncertainty concerns when the innovations or discoveries will become available. Most empirical studies use forms of the lag structure (inverted V, trapezoidal, etc.) which have an initial period in which the investment produces limited results; this is the *gestation period*. This practice meets the need for a succinct and correct description of the effects over time, but it has nothing to do with research uncertainty.[17] The peculiarity of the R&D gestation period is its uncertain length; this uncertainty also implies that some research programmes may actually never go further that their gestation periods: in other words, they fail.

Following this argument, we can divide the service life of a research investment into two phases. The first concerns the technically requisite period before any result is obtained and new knowledge produced. The length of this period is stochastic. The second period is the service life of the new knowledge stock: R&D begins to produce results and these cumulate in the knowledge stock. This is the period when the innovation enters production, generating positive effects (an increase in the TFP). This impact declines over time, but it can potentially last forever unless technological upgrading accelerates its obsolescence.

Equation (8) generally describes how efficiency varies with the investment age. It is also called the aggregate *age/efficiency function* (Hulten and Wykoff, 1996). The series of weights can therefore be expressed as an efficiency function specific of any investment of a given type and vintage (Harper, 1982; Hulten and Wykoff, 1996). In order to take account of the two phases mentioned above, we express the weights as follows:

$$w_s = 0, \qquad s = 0$$

(13) $$w_s = [(1-b)s]/[(G - b\,s)], \qquad 0 < s < G$$

$$w_s = 1, \qquad s = G$$

$$w_s = \prod_{i=G+1}^{s} (1 - d_i), \quad \forall\, i \in [G+1, \ldots, s] \qquad s > G$$

where s is the age, G the length of gestation, d_i the decay rate for any year i of service life calculated as in equation (12), and b a parameter controlling the form of the efficiency over time during gestation; i.e., for s<G (figure 1). $b=0$ implies a linear pattern corresponding to a constant growth rate $1/G$. With $b<0$, the *age/efficiency* curve is concave, that is, efficiency grows at a decreasing rate and the more so the larger the (absolute value) of b. If $0<b<1$, the curve is convex: most efficiency is gained towards the end of the gestation period, and the closer b to 1 the more pronounced the efficiency gains towards G. Finally, if $b=1$ we have the *one-hoss shay* case where efficiency is zero for the whole gestation period. The $0<b<1$ case seems the most plausible, since it takes account of the technical and time constraints always present in the early years of a research programme.

At this stage, a common practice is to fix b and G (Park, 1995), based on the type of research programme, and calculate the series of the weights using equation (13). This approach implies that all homogeneous and contemporary research investments will simultaneously achieve full efficiency after *G* years. This deterministic notion of gestation is rather strong. To relax it, we assume that the gestation length is stochastic, which implies giving equation (13) a probability basis. If we assume that the investment gestation length follows a normal distribution with expected value μ and standard deviation σ, then:

(14) $P(G)=(2\pi\sigma^{2})^{-.5}exp[-(G-\mu)^{2}/2\sigma^{2}]$

yields, for all G, a positive value of the density function and a non-null probability of that event for any interval around G.

One problem with (14) is that the distribution tails go to infinity. Heuristically, we skip the extreme outcomes and focus only on gestations within a finite interval which is of given width and symmetric about the mean. Consequently, we rule out the possibility for an investment to be effective for $s<0$ and for gestation to last indefinitely. In practice, we must define the width (Δ) of this interval, truncate the distribution at $\mu \pm \Delta$, and upgrade the residual area to unity.[18] The truncation has an economic justification, too. Before the lower bound μ-Δ, research can not produce any result. This required minimum (*latency*) period precedes the gestation. The upper bound $\mu+\Delta$, in turn, imposes that the research must reach its full efficiency within a maximum lag, otherwise it will be abandoned.

During the possible gestation period 2Δ, the age/efficiency function can be defined as a weighted sum of the elementary functions (with the same *b*) associated with any event included in the given interval; any elementary function is weighted by the probability computed by the truncated normal distribution. Formally:

$$(15) \qquad w(s|b,D,m,s) = \int_{m-\Delta}^{m+\Delta} w(s|b,G)P(G|D,m,s)dG,$$

$$w(s|b,G) = 0 \;\; for \;\; s \text{ ³ } G \quad \text{and} \quad G = m + D$$

where $w(.)$ is the elementary age/efficiency function (with parameters b and G) described in equation (13), and $P(.)$ is the truncated density function generating the weights, given μ, σ and Δ. The second relation in equation (15) is added in order to explicitly consider the case of failure of the research programme whenever gestation overcomes its maximum length.[19]

Note that equation (15) implies that, in any year, investment efficiency is the sum of weights w_s for that year associated with any probabilistic event weighted by the probability of its occurrence. However, there is only one year in which, for any possible event, full efficiency (w_s = 1) is reached, and this year evidently differs among events. Therefore, if we exclude the special case of deterministic gestation, the age/efficiency function never reaches unity. After all, equation (15) expresses the impact of R&D on the knowledge stock over the years following its accomplishment. It does not describe how its efficiency declines over time starting from the full-efficiency of the initial year, i.e. brand-new capital, as is usually understood where physical assets are concerned (Caiumi *et al*., 1995). In view of the particular economic meaning that attaches to equation (15), it can be better described as the *age/effectiveness function* of the R&D investment.

3.3. User's cost of technological stock

The foregoing analysis of the formation of the knowledge stock does not resolve the issue of the correct measurement of this asset. In fact, the input T to the production function (1) is not the productive stock but, more correctly, the value of the associated service

(Jorgenson, 1989); this is given in turn by the stock itself multiplied by its price or user's cost. However, as regards this particular asset, what price means is not so obvious; it should indicate the cost of using the capital for a given period. However, in this case we cannot appeal to a hypothetical second-hand market, since generally speaking and unlike the physical capital, knowledge capital is not easily marketable.

Yet also the knowledge stock has an implicit price, which is given by the current value of all the service it can provide in the future. This user's cost is determined by three components (Caiumi *et al*., 1995): the opportunity cost of the invested money, capital gains or losses caused by inflation, and capital depreciation. Jorgenson (1989) proposes this specification of the user's cost U:

$$(16) \qquad U_t = P_{t-1}[i_t - p_t + (1+p_t) r_t]$$

where P is the expenditure for the investment, i is the interest rate, p is the expected capital gain (or loss) rate due to inflation, and r is the *depreciation rate.* In this equation, $P_{t-1}(i_t - p_t)$ expresses the opportunity cost in the real terms of a unit of invested capital, while $P_{t-1}(1+p_t) r_t$ is the depreciation corrected for inflation.

The depreciation rate can be computed from the depreciated value of the stock at time t, TW_t:

$$(17) \qquad TW_t = q_0 R_t + q_1 R_{t-1} + .. + q_s R_{t-s}$$

where q_s is the *age/price function*; that is, the ratio between the value of a s-year-old unit of capital and its brand-new price. Recalling Harper (1982), q_s can be calculated as follows:

$$(18) \qquad q_s = \frac{\sum_{h=s} w_h \left[1-r\right]^{(h-s)}}{\sum_{h=0} w_h \left[1-r\right]^{h}}, \quad s \geq 0$$

where r is the long-run discount rate in real terms (assumed equal to 0.04) and w_s is the *age/effectiveness function* according to equation (15).

Finally, economic amortisation D_t is given by the difference between the gross investment and the variation of the depreciated value of the stock:

(19) $D_t = R_t - (TW_t - TW_{t-1})$

It follows that the deprecation rate is[20]:

(20) $r_t = D_t / T_{t-1}$

It is thus possible, given the time series of the knowledge capital stock and user's cost, to calculate the value of its services:

(21) $V_t = U_t \cdot T_t$

4. An empirical application

The purpose of the above analytical framework has been to provide a logical basis for the relation between R&D investment and the formation of the knowledge stock. This relation is expressed by a function describing how research produces new knowledge over time, and it is characterised by some basic parameters resulting from the inherent nature of the research programme. Empirically, one can proceed in two distinct ways. Either we can assume these parameters are known and build the stock according to (15), or, if an estimate of the age/effectiveness function is available, this can be used to identify the underlying unknown parameters. These two applications will be discussed in the following sections.

4.1. Basic research, applied research and development

The relevant parameters b, D, m, s and d^* depend on the technical and economic characters, *sensu latu*, of the investment, namely, the potential fertility of the research, the innovative character and the inherent uncertainty of the research programme, the institutional functioning of the research sector (private-public system), amongst others. Each parameter has an economic interpretation. b sets up the distribution of the efficiency gains during the gestation period, that is the preliminary effort, required to obtain some result; the closer b to unity the more unlikely anticipated results will be. D is the truncation parameter indicating the length of both the latency period and the failure of the research programme. m is the expected value of the gestation period, while s is the standard error indicating the uncertainty, and therefore the risk, associated with the investment. Finally, d^* indicates the initial decay rate, expressing both the obsolescence and the maintenance investment related to the new knowledge.

These aspects are summed up by the traditional distinction among basic research, applied research and development, since different parameter values correspond to the three research categories. According to the Japan Economic Institute (1996) the decay rate d varies between 0.25 and 0.1, and the expected gestation period m between 4 and 7 years.[21] This interval includes most of the values normally assumed in empirical analysis (Namatame, 1989; Park, 1995). Jovanovic and Nyarko (1998) report that the value frequently assumed in empirical research is 0.15. However, owing to the problems mentioned above, few estimates are available. Naidiri and Prucha (1996) report an estimate of 0.12 for the U.S. manufacturing sector, while in an earlier study Pakes and Schakerman (1984) reported values ranging between 0.18 and 0.36, with an average of 0,25. These estimates depend on the type of research: the more basic the research, the smaller the d and the larger the m.

Unfortunately, the literature does not give clear cut indications on the remaining parameters. Consequently, we base our choice on some general considerations. Recalling that the more theoretical, original and borderline the research programme, the greater the uncertainty, and therefore the risk, we express s as a function of m. By the same token, we let D depend on s,[22] so that also the latency and the failure periods depend on the research type.[23] Finally, for b we assume that the age/effectiveness profile during gestation is close to the one-hoss shay case, and the more so the more basic the research programme[24]; in this case it is more difficult to achieve anticipated results.

The select values are reported in the following table:

R&S	β	δ*	μ	σ	Δ	μ-Δ	μ+Δ
Basic	0.98	0.10	7	0.5μ	2σ	0	14
Applied	0.95	0.20	6	0.4μ	2σ	1.2	10.8
Development	0.90	0.25	4	0.3μ	2σ	1.6	6.4

Note that only the initial value δ* is set up, since obsolescence accelerates according to the speed of technological upgrading according to equation (12).[25] The speed of technological upgrading can be approximated by the rate of long-run technical change understood as a permanent gain in productivity due to the shift to the new technological levels. We therefore assume that this speed equals the technical change rate computed, for Italian agriculture, in Esposti (2000c) by means of a signal extraction from the TFP growth guided by R&D investments and free from short-run productivity shocks.[26] In this sense, obsolescence depends on past research investments, and is therefore endogenous.

The age/effectiveness and age/price functions, based on the above parameters and equations (15) and (18), are reported in table 1 and in figures 2 and 3. The weight series differ markedly across research classification, although the bell-shape persists. After twenty years, the effect of applied research and development is almost nill, whereas it is still quite substantial for basic research. Furthermore, maximum effectiveness is reached after five years by development investments, after eight years by applied research, and after eleven years by basic research. As expected, the maximum impact is slightly lagged if compared to the expected length of the gestation. Moreover, the age/effectiveness function is always less than 1 due to the stochastic gestation period. The lower the uncertainty and therefore the variance, the more clear-cut the year of maximum effect will be, and therefore the closer the respective weight to unity: this is clearly the case of investments in development.

Finally, it is worth noting that the age/price function expresses a crucial aspect of the peculiar timing of research results. By definition, the function has value 1 when the investment takes place, but this is not its maximum value, as it is in the case of physical assets. The maximum user's cost is reached after few years: that is, when the current value of the future benefits is maximum. This happens because the research benefits are poor in the early years. They then rapidly increase until the end of the gestation, and deteriorate again in the late years of the service life.

4.2. The Italian case

This section presents an application to public R&D in Italian agriculture.[27] Information comes from INEA (National Institute of Agricultural Economics), CNR (National Research Council) and ministerial accounts (Ministry of Agriculture and Ministry of Scientific and Technologic Research) or accounts of other public institutions involved in agricultural research. Data refer to research funding by the Ministry of Agriculture and Forestry and expenditure by both specialised public research institutes and public university faculties of agriculture and animal science. In addition, also public expenditure in extension is considered. Expenditures are expressed in billions of 1985 Italian lire and cover the years 1956 to 1996.[28] As a fourteen-year gestation length is admitted for basic research, stock can be built from 1970 onwards.

Figure 4 shows the pattern of knowledge stock by type (basic research, applied research and development), under the working assumption that all R&D is in turn of the same type. Comparatively, basic research generates somewhat more stock, especially in the late years of the sample. As mentioned, this difference in the stock measure also affects the estimated internal rate of return.[29] Obviously, the above assumption is strong and unrealistic. The public research effort in Italian agriculture is of course a mix of basic and applied research and development. However, the available aggregate data do not allow a distinction to be drawn among various research types in Italy. The requisite standard according to the Frascati Manual (OECD, 1994) and accepted at the international level cannot be obtained using the above-mentioned data sources because they normally report data by funded organisation rather than by funded research programme.

To bring the stock closer to the actual research mix, we assume that the classification by funding institution largely corresponds to the classification by research type. According to the Frascati Manual, basic research is not targeted on some predetermined use. We may therefore assume that it largely corresponds to research conducted within the university system. Applied research is associated with the activities of non-academic public institutes and organisations, since these mainly carry on closely targeted research.[30] Finally, development is associated to activities carried out through extension expenditure. On these assumptions, the three stocks can be calculated, and each of them corresponds to the contribution made by the respective research type: their sum is therefore the mixed knowledge stock. Note that the stock of development prevails until the nineties and then, the basic research stock becomes predominant. The development stock remains constant from the mid-eighties onwards, and it is equalled by the applied research stock in the mid-nineties (figure 5).

4.3. Parameter calibration

From the previous section, two main aspects emerge in the definition of the knowledge stock: the parameters underlying the lag structure and the expenditure shares of each research type. Some assumptions were made concerning both aspects in order to enable calculation of the stock. These assumptions are to some extent arbitrary. In principle, however, the model can also be used to move in the opposite direction: that is, to estimate parameters and shares or to test the reliability of the hypotheses. Suppose that we have an estimate $\overline{W}_s$ of the weights relative to public R&D in Italian agriculture. According to the model described, these series are the weighted sum of the w_S from equation (15) associated with any investment type; that is:

(22) $$W_s = \left(q^B w_s^B + q^A w_s^A + q^S w_s^S\right), \qquad (q^B + q^A + q^S) = 1$$

where q^B, q^A and q^S are the shares in total R&D expenditure of basic research, applied research and development respectively, while w_s^B , w_s^A and w_s^S are the relative weights according to equation (15). Therefore, a minimum least squares criterion can be used to estimate the unknown parameters:

(23) $$\min_{b,d,\Delta,m,s,q^B,q^A,q^S} \left\lfloor \sum\nolimits_s (\overline{W}_s - W_s)^2 : (15), (22) \right\rfloor$$

This empirical solution, however, is not usually feasible. Firstly, a reliable estimation of the vector $\overline{W_s}$ should be obtained, but this is no easy task considering the problems outlined in section 2. As mentioned, the nonparametric approach seems appropriate since it does not impose constrains on the lag structure. Esposti (2000b) has used this approach to derive $\overline{W_s}$ for Italian public agricultural research. This estimate can be referred to a 20-year maximum lag. A second and major problem, however, arises because equation (23) is markedly non-linear in the parameters, and the traditional econometric methods are of little help. Moreover, we may expect major identification problems to occur: the same vector of weights W_s may be caused by many, or infinite, combinations of parameters and shares of the three research types. In fact, the lag structure observed is determined by a vector of parameters which does not correspond to any vector of the research types: the research mix will in turn imply a mixed aggregate set of parameters.

Figure 6a compares the 'hybrid' lag structure drawn using the nonparametric approach with the ones implied by the three research types.[31] Summing the squares of the deviations (ESS) between estimated and expected weights allows us to conclude that the case that comes closest to the observed weights is applied research. As pointed out, however, the structure observed is actually a 'hybrid' and could also be generated by a mix among the types, bringing the combination of the parameters close to the case of applied research even when this has a limited role.

Even in the case of under-identification, it is possible to calibrate the set of these 'hybrid' parameters by moving around the grid of the predetermined intervals outlined in section 4.1. Of the different possible combinations, the one with the lowest ESS is chosen. Figure 6b shows this case, which comes quite close to the observed structure, confirming the reliability of the selected parameters and implying a combination of parameters that does not correspond to any type. According to this calibration, the expected value of the gestation period is six years, and the early results in this period are rather poor; these features make the mix closer to basic research. However, the obsolescence rate and uncertainty are closer to what one would expect as regard development. Therefore, the 'hybrid' character of the underlying public agricultural research investment in Italy is confirmed by the data. This feature does not derive from the alleged objectives of the research programmes funded but is a feature of the research results themselves.

5. Concluding remarks

The main purpose of this paper has been to address the issue of how to build the R&D stock from the flow of gross investments. This topic is much discussed in the recent agricultural economics literature because R&D expenditure is a major source of sectoral technical change. Furthermore, a large, if not predominant, amount of this research effort is based on public funding, so that a correct measure of its real impact on production is obviously needed. Computing this impact, however, depends largely on how the research stock is built.

On this point, however, a number of econometric difficulties make this task particularly challenging. An alternative approach is to depict those features of the research stock that make it substantially different from the physical asset, and to propose an analytical framework which recovers the stock on the basis of a set of basic parameters with a clear economic interpretation. Moreover, these parameters differ among basic research, applied research and development.

The Italian case shows how, keeping the gross investment constant, different hypotheses about these parameters can significantly affect calculation of the stock and, consequently, estimation of the rate of return on R&D. Empirical identification of the basic parameters is difficult, partly because detailed data on the features of funded research programmes are lacking. The model's calibration, however, supports the idea of 'hybrid' research involving the presence of all the various R&D types and confirming the model's ability to approximate the lag structure observed, given an appropriate vector of parameters.

Besides these results, the paper has presented an approach, which suggests further empirical analysis of the impact of R&D investments and the returns on them, following two distinct lines of inquiry. Firstly, the lag structure of the effect of R&D over time can be recovered by defining its type, and therefore by making assumptions about the basic parameters. This line of inquiry requires more detailed data collection on research expenditure and further research into the economic aspects that affect the character and value of the parameters themselves.

Alternatively, the approach proposed can be used to estimate, rather than assume, the parameters mentioned in order to detect the underlying features of the research effort. However, in this case estimation of the weights is necessary, which in turn requires a long R&D series. Secondly, recovering the basic parameters using traditional econometric tools is a very difficult task. Nevertheless, this seems to be an interesting area for further research.

[1] Although extremely simple, this function is still widely adopted (Jones and Williams, 1998; Griliches, 1998).

[2] The conversion of these benefits into monetary values is trivial because the TFP growth can be directly interpreted as the growth rate of production or the rate of cost reduction.

[3] The alternative is to directly estimate equation (5), or its dual (Bernstain and Nadiri, 1989; Morrison and Siegel, 1998; Esposti and Pierani, 2000a) known as the *integral approach*; otherwise estimate equation (6) or (7) after calculating the TFP growth, known as *two-stage approach*. In this latter case, measurment errors in the TFP calculation (Antle e Capalbo, 1988) may generate inconsistent estimates (Esposti e Pierani, 2000b).

[4] There is also an attribution problem among groups: that is, among different sources of the research effort (Alston and Pardey, 2000). This issue concerns the computation of technological spillover, both international and intersectoral, which is not dealt with in detail here. For more information on this aspect with reference to Italian agriculture see Esposti (2000a).

[5] Especially when public agriculture research is being studied, many authors suggest that the effects can last longer than thirty years (Alston *et al*., 1998; Chavas *et al*., 1997; Pardey and Craig, 1989).

[6] Frequently assumed forms are the inverted V, the trapezoidal, the polinomial, etc. (Alston and Pardey, 2000) or simply the PIM itself, as in Nadiri and Prucha (1996).

[7] According to Alston and Pardey (2000), the truncation of the lag structure at 15 or 20 years (which is a frequent practice due to the short R&D series usually available) often causes an earlier attribution of the research benefits over time and, in turn, an overestimation of the return on R&D. A recent example of this kind of problem is Fan (2000).

[8] Estimating the relation in the first differences, that is equation (7), can solve the problem only if the TFP and the knowledge stock are not cointegrated. In the case of cointegration, a specification of the model in the error correction form would be needed (Makki *et al*., 1999) and estimation of equation (7) would incur specification errors (Plosser and Schwert, 1978; Enders, 1995).

[9] In short, we may say that the problem must be tackled in the field of the *economics of science* rather than of *econometrics*.

[10] A classic example in agriculture is provided by single and specific research programmes carried out in order to select new improved varieties whose sequence of research results over time can usually be recovered in detail (parental lines, hybrids, new varieties etc.). A valuable reference is Pardey *et al*. (1996).

[11] The depreciation is the loss of economic value of the asset, and therefore refers to the capital service, while the decrease in the stock quantity should more properly be called 'decay' (Hulten and Wykoff, 1996).

[12] Agriculture provides numerous examples. For instance, the technological knowledge associated with traditional and local cattle breeds has become obsolete with the introduction of new improved breeds. Analogously, technological knowledge regarding some species of vine and wine processing loses its value when consumers show less preference for these products. However, in neither of these cases does this imply that the underlying knowledge is entirely lost.

[13] Alston *et al*. (2000) adopt an analogous solution based on a similar argument.

[14] Park (1995) admits a m-years lag in the effects of the research investment, and the equation (9) becomes $T_t = T_{t-1}(1-d) + R_{t-m}$.

[15] In agriculture an example of this decay concerns new improved varieties. In recent decades the introduction of new varieties has occurred at increasing rates in the developed countries, but their turnover has accelerated at the same time. In the USA, five new wheat varieties were introduced on average each year in the period 1900-1970; since 1970 this average has increased to twenty-one new varieties but their turnover is now less than five years. As reported by Pardey *et al.* (1996), most of these recent varieties have been obtained by introducing incremental improvement on a common original base given by the varieties selected in the late sixties at the CIMMYT (International Wheat and Maize Improvement Center) in Mexico. Therefore, most of the innovation embodied in recent varieties has a short life indeed; only some of it remains enduringly useful since it constitutes the original radical innovation.

[16] This is the well known hypothesis of R&D decreasing marginal returns in the creation of new knowledge (Evenson, 1984; Jones, 1995; Griliches, 1998 cap. 12). These returns should not be confused with R&D return with respect to productivity according to equation (7). However, these two concepts are obviously related, because decreasing returns on the R&D in the generation of knowledge also induce decreasing returns on research to increase productivity.

[17] Actually, a similar argument is also valid for investments in physical capital which require an initial start-up period.

[18] For technical details see Caiumi *et al*. (1995).

[19] The integral does not have an analytical solution because the integrand function is not continuous for any vintage. It has therefore been numerically approximated with the Simpson method (Johnson e Rees, 1982).

[20] r differs from d because it refers to the loss of economic value and not to loss of efficiency. Note that geometric decay (d) has a self-dual property because it implies geometric depreciation (r) (Hulten and Wykoff, 1996). This also emerges clearly from the results in the next section.

[21] The JEI estimates rely on several sectors and countries. They may thus be regarded as references of general validity (Castaldi and Levialdi, 1997).

[22] D and s as functions of m are often also adopted in the definition of the stochastic service life of the physical asset. For an application to Italian agriculture see Caiumi *et al*. (1995); these authors assume $D=2s$ and $s=0,5m$ for agricultural physical stocks.

[23] On these assumptions, basic research, because it is more innovative and riskier, implies a greater m and consequently greater D and s. It also follows that the possible interval of gestation is 14 years wide.

[24] In any case, the hypothesis that early results during gestation are relatively hard to obtain is maintained; they are mainly concentrated in its late part. Therefore, regardless of the research type, the parameter varies within an interval quite close to unity (that is close to the one-hoss shay case).

[25] Note that if we consider the first fifteen years after the end of gestation, and on the basis of the assumption on technological upgrading, the adopted δ*'s correspond to these respective average δ's: 0.12; 0.23; 0.30. These values come quite close to the range estimated by Pakes and Schankerman (1984) and Nadiri and Prucha (1996).

[26] Estimated long-run technical change rate in Italian agriculture in the period 1971-1991 was 0.023. Therefore, the proxied speed of technological upgrading is $\left[f\left(t, \sum_t R_t\right)\right] = 0{,}023$

[27] In a narrow sense, private agricultural research is not significant in Italy. However, a broader interpretation of private agricultural research sometimes includes R&D effort by the food industry and by industries specifically producing inputs for agriculture (chemicals, machinery, drugs, etc.). However, it is more appropriate to refer to these cases as intersectoral technological spillover (Esposti, 2000a).

[28] For a more detailed description of the R&D data and the various sources of public research expenditure in Italian agriculture see Galante and Sala (1989).

[29] For instance, by estimating equation (7) for the three hypotheses of research stock, internal rates of return of 23% (basic), 18% (applied) and 49% (development) are obtained. Despite the problems of specifying the estimated model and of measuring the TFP, these results show that estimation of the rate of return may be affected by the assumed lag structure for the same gross investment flow.

[30] The main non-academic public research institutes and organisations in Italian agriculture devote their efforts mostly to well-targeted programmes. This is the case of the IPRA and RAISA projects of the CNR and the Ministry Experimental Centres closely specialised in some crop or production.

[31] To enable comparison, the $\overline{W_s}$ and W_s series have been indexed with respect to the maximum value of the relative lag structure. The truncation at the twentieth lagged year does not mean that the weight in this year is imposed as 0; that is, no *end-point restriction* has been introduced. However, the truncation is necessary because the nonparametric analysis is bounded by the shortness of the R&D series (Esposti, 2000b).

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Table 1: Age/effectiveness (w_s) and age/price (q_s) functions of the R&D investment

AGE	BASIC Stock (ω_s x100)	BASIC Price (θ_s x100)	APPLIED Stock (ω_s x100)	APPLIED Price (θ_s x100)	DEVELOPMENT Stock (ω_s x100)	DEVELOPMENT Price (θ_s x100)
0	0,50	100,00	0,00	100,00	0,00	100,00
1	4,38	104,07	1,89	104,17	3,62	104,17
2	7,38	107,53	8,72	107,94	13,19	107,27
3	15,38	110,54	15,02	109,84	47,31	107,22
4	20,33	112,09	29,97	109,95	63,00	95,49
5	32,20	112,71	37,77	105,60	74,87	77,89
6	37,67	110,99	52,88	98,75	55,09	55,55
7	49,62	108,12	54,04	87,11	40,73	39,16
8	52,87	102,75	57,15	74,64	29,88	27,16
9	60,16	96,50	50,27	60,72	21,73	18,52
10	60,51	88,55	43,86	48,28	15,67	12,40
11	60,52	80,39	34,30	37,22	11,20	8,15
12	56,68	71,69	26,78	28,55	7,93	5,25
13	53,36	63,40	20,78	21,77	5,56	3,32
14	47,28	55,41	16,02	16,48	3,87	2,05
15	41,86	48,31	12,26	12,40	2,66	1,24
16	36,95	41,99	9,33	9,26	1,81	0,73
17	32,51	36,38	7,04	6,87	1,22	0,42
18	28,53	31,43	5,28	5,06	0,81	0,24
19	24,95	27,06	3,93	3,70	0,53	0,13
20	21,75	23,22	2,90	2,68	0,35	0,07
21	18,90	19,85	2,12	1,93	0,22	0,04
22	16,37	16,92	1,54	1,38	0,14	0,02
23	14,13	14,37	1,11	0,97	0,09	0,01
24	12,15	12,15	0,79	0,68	0,05	0,00
25	10,41	10,24	0,56	0,47	0,03	0,00
26	8,89	8,59	0,39	0,33	0,02	0,00
27	7,56	7,18	0,27	0,22	0,01	0,00
28	6,40	5,98	0,19	0,15	0,01	0,00
29	5,40	4,95	0,13	0,10	0,00	0,00
30	4,54	4,08	0,09	0,07	0,00	0,00
31	3,80	3,35	0,06	0,04	0,00	0,00
32	3,16	2,73	0,04	0,03	0,00	0,00
33	2,62	2,22	0,02	0,02	0,00	0,00
34	2,17	1,79	0,02	0,01	0,00	0,00
35	1,78	1,43	0,01	0,01	0,00	0,00
36	1,46	1,13	0,01	0,00	0,00	0,00
37	1,18	0,89	0,00	0,00	0,00	0,00
38	0,96	0,69	0,00	0,00	0,00	0,00
39	0,77	0,53	0,00	0,00	0,00	0,00
40	0,62	0,40	0,00	0,00	0,00	0,00
41	0,49	0,29	0,00	0,00	0,00	0,00
42	0,39	0,21	0,00	0,00	0,00	0,00
43	0,31	0,14	0,00	0,00	0,00	0,00
44	0,24	0,08	0,00	0,00	0,00	0,00

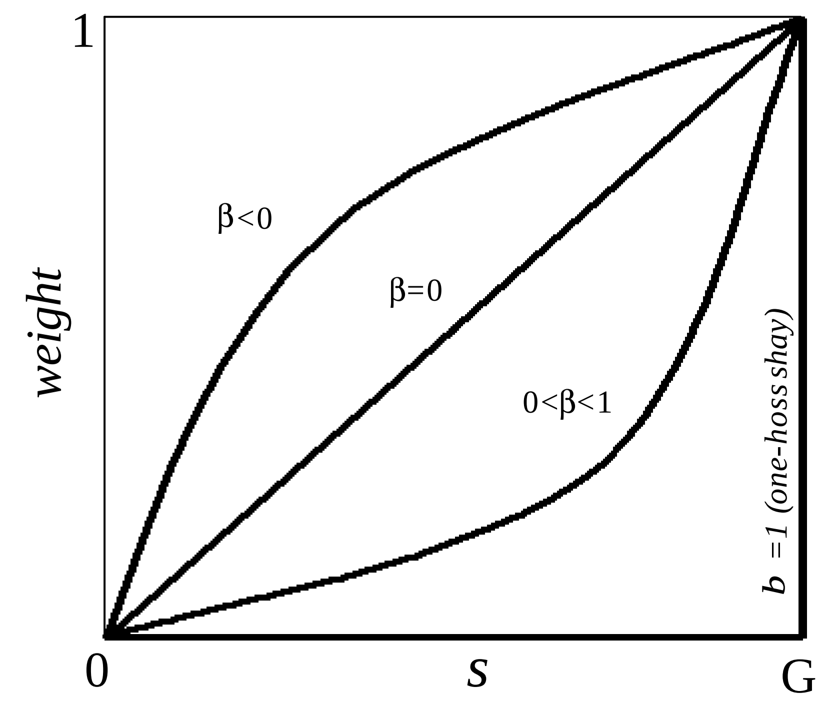

Figure 1 – Relative effectiveness of the R&D investment with gestation G, under different values of ***b***

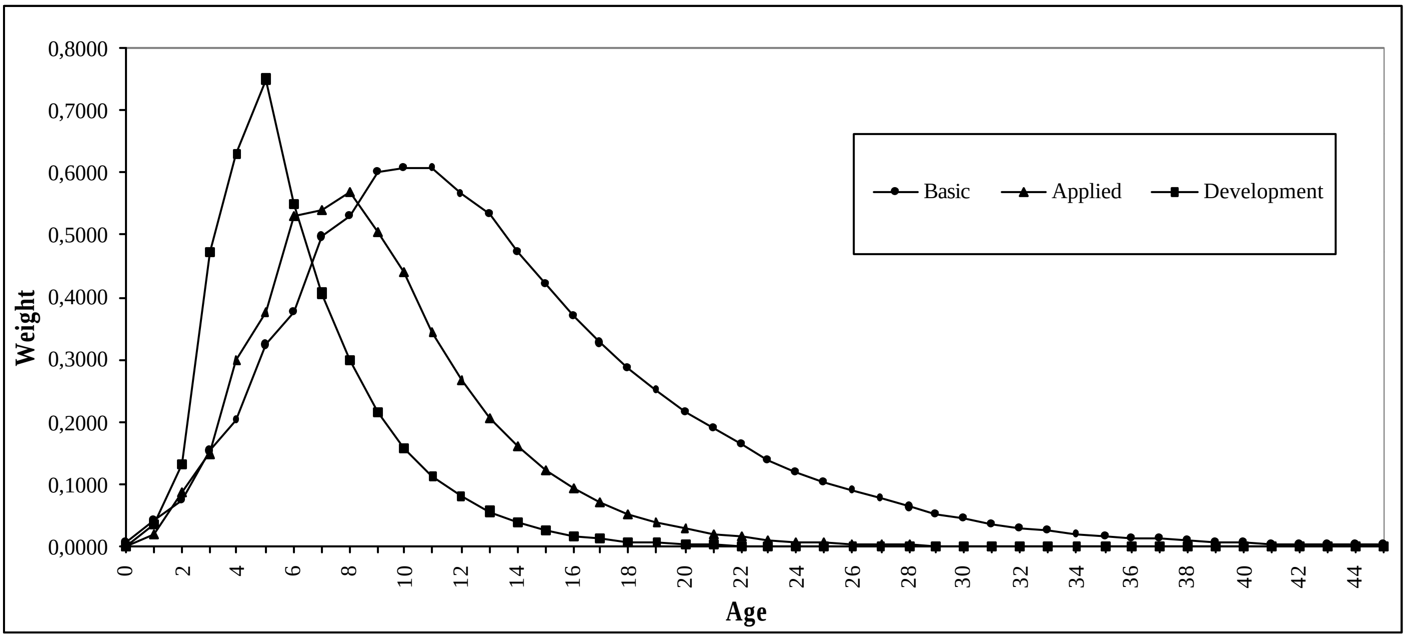

Figure 2: Age/effectiveness function by investment type

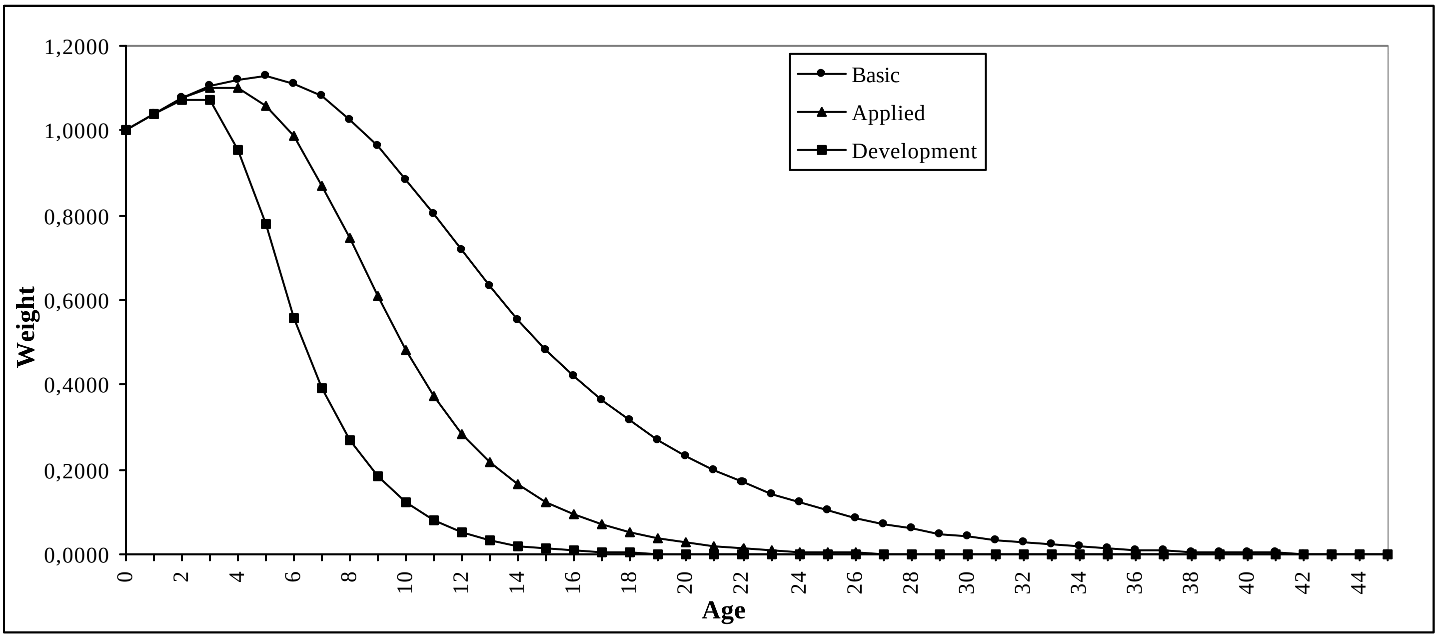

Figure 3: Age/price function by investment type

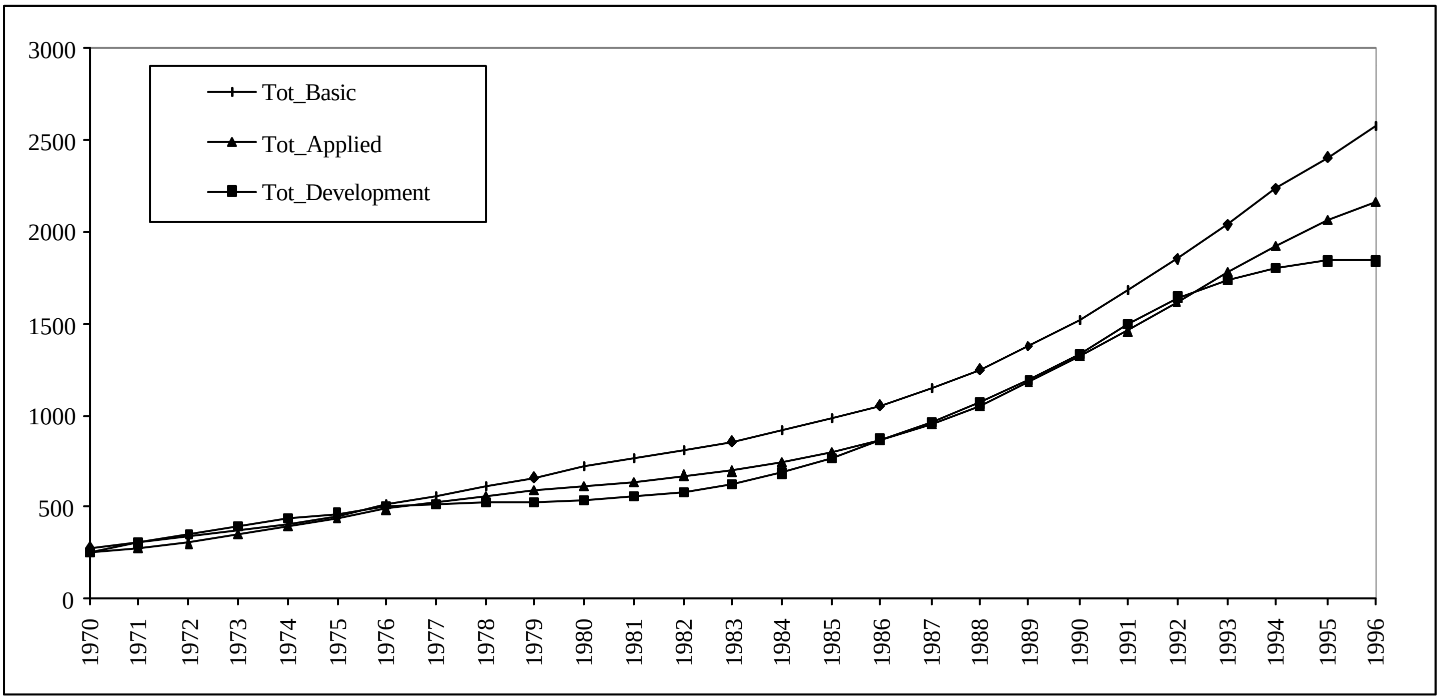

Figure 4: R&D stock under the three typological hypotheses (1985 billions of Italian Lire)

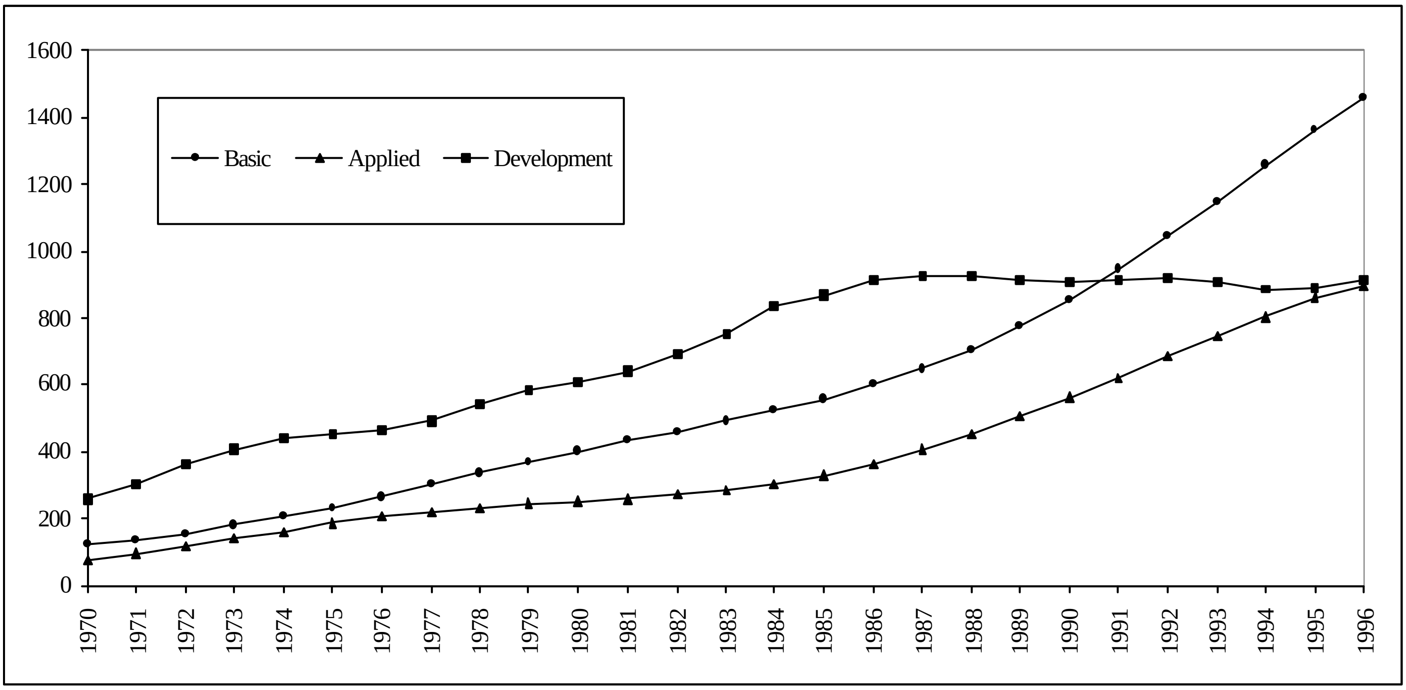

Figure 5: Series of the three stock typologies (1985 billions of Italian Lire)

Figure 6a – Lag structure under non parametric estimation and various R&D hypotheses

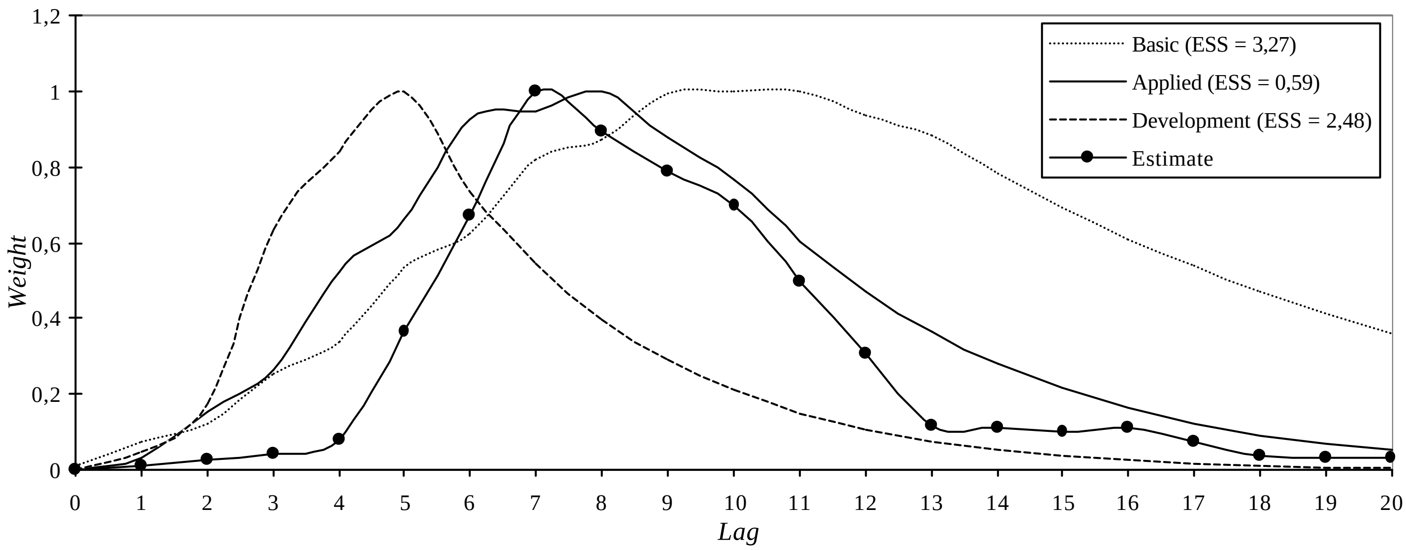

Figure 6b – Lag structure under nonparametric estimation and calibration of the parameters