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Public R&D and European agriculture: impact on productivity and return on R&D expenditure

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Abstract. While higher effort in research is advocated for agriculture, there continues to be a lack of measurement of its impact in economic terms, at least in Europe. This paper seeks to assess the economic impact of public agricultural R&D investments in Europe. Different panel models are applied on 16 European countries, by employing productivity and investment data. Results show positive impacts with returns on public R&D investments on agricultural productivity of between 6.5% and 15.2%, varying according to model specifications and computation techniques. These values confirm that research expenditure in agriculture is well justified in economic terms. However, the results are highly dependent on the analytical approach and limited by the paucity of expenditure data. Further research is recommended to take into account the role of other important determinants of impact, such as climate, spill overs and the Common Agricultural Policy (CAP). However, a proper consideration of these variables will first require a major improvement of data availability.

Keywords: public R&D investments, agricultural productivity, rate of return, Europe.
JEL Codes: O33, O47, Q16.

1. INTRODUCTION

Public agricultural research investments in developed countries has shown contrasting trends in recent decades, including a reduction in some documented cases (Hurley et al., 2016; Pardey et al., 2016; Rao et al., 2016; Pardey et al., 2018). While the reasons for current trends in public R&D investment in developed countries can be debated, representing a paradox (Alston, 2018), institutional and political reforms are in place in middle-income countries aimed at supporting both research and agricultural productivity (Wang et al., 2012; Fuglie, 2016). At the same time, private investments in research and development (R&D) in the agri-food sector notably increased, especially in upper middle-income countries (Pardey et al., 2018).

It is well known, since the first study by Griliches (1958), that public investments in agricultural research are highly profitable in the long run (Alston et al., 2000; Piesse et al. 2010; Hurley et al., 2014) and are acknowledged to be a fundamental driver for the improvement of agricultural pro-

ductivity (Ball et al., 2001; Ball et al., 2010). At the same time, the literature admits the limitations and, in many cases, the lack of reliability of the agricultural productivity measurements as well as their difficulty in representing the actual evolution of the agricultural sector and the profitability thereof (Alston et al., 2010; Wang et al., 2012; Hurley et al., 2014; Rao et al., 2016). Better measurements and more reliable estimates of agricultural productivity and rates of returns (RoR) would be helpful in guiding public investment choices. Indeed, the improvement of methodologies for quantifying the impact on agricultural productivity, with the aim of precisely estimating the RoR of research investments in agriculture, is an issue that has been challenging economists for a long time, especially in developed countries. Indeed, the ongoing literature discussion (Davis, 1981; Alston et al., 2000; Hurley et al., 2014; Oehmke, 2016; Hurley et al., 2016b) is still focusing on adjusting the RoR estimates because they are considered, for several technical reasons, (upward) biased and hence not fully reliable. However, in Europe, recent evidence of returns on public investments in agricultural R&D are scarce because of limited data availability.

Besides the difficulty of establishing a connection between R&D expenditure and productivity, the literature observes a change in focus of European agricultural policies (and public R&D effort) from purely productivity-focused objectives towards guaranteeing the environmental sustainability of agricultural production, the health and safety aspects of food and feed production, along with other aspects related to the degree of protection and promotion of public goods[1] (Gardner and Lesser, 2003). In contrast, the more production-oriented investments in agricultural R&D are 'left' to the interest of private (business) investors (Pardey et al., 2018). Further, scientific evidence from the InSTePP database (Pardey et al., 2018) reveals that part of the R&D investments in agriculture are devoted to "maintenance" of productivity levels obtained in previous years.

The objectives of this paper are to assess the contribution of public investments in agricultural research to agricultural productivity in Europe, through a quantitative analysis, and to measure the economic impact of research expenditure in terms of RoR.

Consistently with this branch of the literature, the focus of the paper is on public expenditure related to agriculture (see section 3 three for more details) and not on research policy (i.e. how money is spent and what

incentive instruments are used)[2]. The main contribution of the paper is on the empirical ground as it contributes to fill a gap in the recent literature, which does not include recent analyses of R&D impacts on European agriculture. In fact, the only 'recent' study addressing the issue is that of Schimmelpfennig et al. (1999), analysing the 20-year period from 1973-1993. In addition, this paper also provides a methodological contribution by tailoring suited analytical methodologies to the limited available data, especially the series on public R&D expenditure in Europe.

This paper proceeds with a section on the review of the relevant literature (section 2), followed by the selection of the available data (section 3) and the presentation of the chosen methodology (section 4). Two subsequent sections provide the illustration of the results (section 5) and related discussion (section 6). The paper ends with a concluding section (section 7).

2. LITERATURE REVIEW

The connection between spending on research and development (R&D) and agricultural productivity has diffused evidence in the literature (Griliches, 1958; Parente, 2001; Hall et al, 2010). The nature of such a connection, firstly explored by Shultz in 1953, is to be referred to what would have been formalized as the *Solow model* after Solow (1957): technological change and inputs are responsible for the long-run variations in rates of growth of output, with technology being the unobserved exogenous factor of the aggregated production function and estimated *ex-post* as *residual*. Applying the Solow model, most studies (Alston et al., 2000; Ball et al., 2001; Fuglie, 2016) measure agricultural productivity by the means of Total or Multi Factor Productivity (TFP or MFP), namely the Solow residual. The computational methods and estimation techniques of the TFP have been largely improved over time (e.g. the aggregation and index numbers and the dual approach, *inter alia*) (Hall et al, 2010). Yet they remain in the framework of the Solow model, therefore treating technology advances – and their causes – as exogenous elements of the models. Such a framework, in fact, completely ignores the decision process of agents and institutions for generating and adopting new technologies and, hence, treats change in technology as a costless factor.

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[1] For a wider and more comprehensive description of recent perspective on these aspects, see the Deliverable 4.2 of IMPRESA project, downloadable at http://www.impresa-project.eu/home.html

[2] For these and more aspects related to institutional aspects and to the relationship between European R&D policies, CAP and more policies the reader might refer to the other documents and publications of the IMPRESA projects.

The further objective of this type of studies is to estimate the rate of return from public investments in agricultural research. Based on the same neoclassical framework, research expenditure is treated as a capital input affecting the agricultural supply function (causing shifts in the supply function) and, therefore, the TFP. The contribution, in terms of effects, of public research expenditure on the evolution (increase) of agricultural productivity is then used as the basis for the computation of the RoR on investment, under a cost-benefit analysis framework.

Alternative theoretical and methodological approaches are applied, instead, for estimating the RoR of private R&D investments (Hall et al., 2010). The main difference rests in the specification of the maximizing behaviour of the firm, which includes elements pertaining to the private sector, such as market power, strategic behaviour, variable return to scale (long-run RoR) and own spill over stocks. Another important distinctive factor is the joint determination of R&D investment and expected RoR, which, in fact, causes the emergence of measurement issues of RoR on private R&D investments as well as manifold interpretations of the estimates, especially of the RoR, due to the condition of endogeneity of the R&D variable.

Common issues to tackle in the evaluation of public and private RoR on R&D investment are the estimation of the rate of return and its interpretation. In fact, both topics are still feeding the academic debate and, despite efforts by Alston et al. (2011) and Hurley et al. (2014) in proposing a more cautious approach for estimating RoR (taking into account reinvestment factors) and for providing results more suitable for plausible interpretations, the issue of correctly estimating RoR remains unresolved. Such an issue appears clearer in the meta-analysis proposed by Alston et al. (2000) and, more recently, in the worldwide collection of RoR studies by InSTePP Returns to Research (RtR) Database (Hurley et al., 2016a). What emerges from these reviews is a likely overestimation of the marginal effects of R&D investments on productivity, which, in turn, affects RoR estimates (Hurley et al., 2014; Oehmke, 2016; Hurley et al., 2016b). In order to try to address this issue, it would be useful to minutely isolate the effects of R&D investments on agricultural productivity by considering potential factors, other than R&D investments, affecting the returns on R&D in agriculture, such as: the intra- and extra-sectorial spill over, the role of the structural transformation in the agricultural sector (Timmer, 1988), the influence of policies on agricultural production and productivity (Restuccia et al., 2008) and the effect of the growing competitive pressure on the European agricultural sector (Galdon-Sanchez, 2002; Schmitz, 2005; Duarte et al., 2010).

3. DATA AVAILABILITY AND SELECTION

To estimate the return to investments in agricultural research, two groups of data are needed: expenditures on agricultural R&D and measures of agricultural productivity. At the European level, data on R&D expenditure are collected according to two main categories: Gross domestic Expenditures on R&D (GERD) and Government Budget Appropriations or Outlays on R&D[3] (GBAORD). GERD data group the actual intramural expenditures on R&D, while GBAORD data refer to all appropriations by central governments allocated to R&D in central government or federal budgets. Unless otherwise stated, GBAORD data include both current and capital expenditure and do not only cover government-financed R&D performed in government establishments, but also government-financed R&D performed in the business enterprise, private non-profit and higher education sectors, as well as abroad[4].

Agricultural GERD time series are difficult to use in econometric analyses, as data are missing for several years, especially before 1996, and several countries do not have any records to speak of. The use of the alternative source, GBAORD data, as an indicator (or measure) of agricultural R&D investment may hold only under the condition of considering solely public R&D investments, provided that GBAORD can represent a reliable proxy of GERD public R&D expenditures. A comparative analysis of public GERD (for all fields of science), revealed that the difference (or divergence), in average terms per country, at the European level is 3% with respect to GBAORD[5]. For this reason, GBAORD data have been considered as a suitable proxy of actual expenditure for the aims of this paper.

GBAORD data are covering all public budget spending related to R&D and are linked to policy issues by means of a classification by "objectives" or "goals". Programmes are allocated between socio-economic objectives on the basis of intentions at the time the funds are committed and not the actual content of the projects concerned. These breakdowns reflect policies at a given

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[3] Since 2019, GBAORD are renamed GBARD: Government Budget Allocations for R&D

[4] This and further methodological information can be found in the revised version of the Frascati Manual, OECD 2002.

[5] For a wider and more comprehensive description of GERD and GBAORD data, see the Deliverable 4.1 of IMPRESA project, downloadable at: http://www.impresa-project.eu/home.html

moment in time. GBAORD data are organized according to NABS.

GBAORD data from 1980 to 2007 on agricultural production and technology are collected according to NABS 92 chapters and sub-chapters:

• General research:
  - Fishing and fish-farming;
  - Crops;
  - Forestry and timber production;
• Animal product:
  - Veterinary medicine;
• Food technology;
• Other research on agricultural production and technology.

GBAORD data since 2008 on agriculture are collected according to the NABS 07 unique chapter Agriculture, which *de facto* aggregate the sub-chapters listed under NABS 92.

For Agriculture, GBAORD data collected according to NABS 92 are available for chapters and sub-chapters, while GBAORD data collected according to NABS 07 are available for the unique chapter[6].

Agricultural productivity series are available from USDA in terms of TFP, computed upon agricultural input and production data, available from FAOSTAT, over the period 1961-2010 for all countries worldwide. Another series of agricultural TFP is available from the KLEMS project (2016), but these differ from the ones computed by the USDA because they take into consideration improvement in qualitative aspects of both agricultural products and inputs. Even if they are apparently an attractive data source for econometric analysis, in light of inclusive of qualitative attributes, the limited series availability for several European countries and the indexation 1995=100 do not allow for KLEMS data to be suitable for quantitative analysis[7]. Based on this, TFP series from USDA have been preferred as productivity measures to be employed in the present study as the data are complete and available for all European countries and the reference value 100 is set in 1961 (out of the observed period[8]).

GBAORD data on agricultural R&D expenditures have been selected from the OECD database because

they are measured in USD and, for this reason, comparable to the production measures provided by FAOSTAT and, in turn, to TFP measure provided by USDA.

The following 16 countries provide for the most complete series of agricultural GBAORD and, hence, have been selected for the aims of the present study: Austria (AT), Belgium (BE), Denmark (DK), Finland (FI), France (FR), Germany (DE), Greece (EL), Ireland (IE), Italy (IT), The Netherlands (NL), Norway (NO), Portugal (PT), Spain (ES), Sweden (SE), Switzerland (CH), and the United Kingdom (UK). For statistical and analytical purposes, the selected countries guarantee a rather good representativeness of Europe, in particular because of the presence in the sample of Nordic, Continental and Mediterranean countries. Complete series of agricultural GBAORD are available starting from 1981 to 2013. However, in order to align them with USDA productivity series, the time series are intentionally selected up to 2010.

Table 1 shows that only six out of sixteen countries – FR, DE, IT, NL, ES and UK – record average agricultural GBAORD values largely over 100 MUSD in the period considered. By looking at physical and economical dimensions (from FAOSTAT), it is possible to note that public agricultural investments, at country level, are to a large extent proportional to both agricultural fixed capital (mainly represented by agricultural land) and the value of agricultural production.

Another factor emerging from the selected sample is the variability per country of the investment in agricultural R&D over time (yearly trend – Aver. % Δ in table 1). The most extreme examples from the selected countries are BE, EL and UK, which have steadily disinvested in agricultural R&D over the last three decades, and AT, FI and NO, which, on the contrary, recorded constant increases. The remaining countries, instead, show intermediate averages generated by alternating periods of increases and decreases in agricultural R&D investments.

An exhaustive presentation of the FAOSTAT production and input data is available on the USDA website (2016) and in Fuglie (2016). Given the objectives of this study, the use of FAOSTAT agricultural data are preferred to Eurostat data since the latter does not provide a complete series over time. Another reason has to do with comparability in constant 2005 USD with R&D investment measures, at least for gross agricultural production (GAP)[9]. A synthetic analysis[10] reveals that FR, DE,

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[6] For further details, please refer to RAMON – *Reference And Management Of Nomenclatures* provided by EUROSTAT.

[7] Despite this, a comparability test has been performed on both datasets to check potential longitudinal differences. To make both series comparable, the data have been transformed in growth terms with respect to the fix year 1980. The equality (t-test) test reveals that the time-series are different in terms of growth trends.

[8] For more details about the computational methodology, visit the USDA website:https://www.ers.usda.gov/data-products/international-agricultural-productivity/documentation-and-methods/ .

[9] TFP measures are computed from GAP, hence allowing for the comparability between TFP and R&D investments.

[10] A detailed descriptive analysis is available at: http://www.impresa-project.eu/home.html, Deliverable 4.1 of IMPRESA project.

Table 1. GBAORD for agriculture – Million 2005 Dollars – Constant prices and PPPs (time averages).

	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland
Mean	41	59	73	80	526	470	51	57
St. Dev.	6.4	20.6	22.7	13.6	170.6	128.1	12.7	27.4
Aver. % Δ[1]	0.80%	-3.87%	1.42%	1.68%	-2.94%	1.82%	-1.82%	4.48%
	Italy	Netherlands	Norway	Portugal	Spain	Sweden	Switzerland	United Kingdom
Mean	277	176	112	107	311	46	47	519
St. Dev.	89.7	37.9	22.1	39.0	240.5	11.9	13.6	105.3
Aver. % Δ	1.54%	0.00%	1.98%	3.13%	7.13%	0.00%	0.00%	-2.07%

Source: own elaboration on OECD data.

[1] Per each country, the trend has been computed linearly through OLS (the estimated coefficient of time) and then averaged by the mean of the series.

IT, NL, ES and UK are the European countries with the highest shares of GAP, having each an average (sample) value over 5%. Cumulatively, these countries cover about 80% of the GAP value of the European agricultural sector and their average GAP trends have been stable over the period 1980-2010. The group formed by the remaining countries, AT, BE, DK, EL, IE, NO, PT, CH, SE and FI, records a global increase in GAP (mostly up to 2000 then flattening or decreasing thereafter). Despite the differences observed at the country level, a weak increase in GAP trends in the 1980-2000 period, followed by a marginally decreasing growth tendency, seems to characterise the general pattern of the agricultural sector at the European level.

The possible determinants of this observed pattern are to be identified in factors underlying production processes that contributed to improve the productivity of inputs (technology, innovations, knowledge…), in other elements characterising the multifunctional nature of the European agricultural sectors (environmental protection, food safety, diversification, climate change) as well as in measures providing constraints (cross-compliance, agro-environmental schemes) or reducing incentives (decoupled payments) to agriculture productivity provided by the Common Agricultural Policy (CAP). The data on R&D expenditure are available at a European level, but considering country level investment in agricultural R&D. Data are not referred to a European Union context, but rather at the country level expenditures. This includes EU funds and the CAP component related to R&D, but it is not explicitly disaggregated. Therefore, we omitted explicit references to CAP or to other related EU policies.

Unlike the GAP and production inputs, TFP is not an observed measure but rather a complex index expressing the relative change, over time, of the technical contribution of production inputs to output. Indeed, the evolution of the TFP index is, as suggested by Fuglie (2016), highly sensitive to R&D investments in terms of both improvement of the production frontier, through *technical change* (by increasing output levels) and rise in input productivity, through *technical and allocative efficiency* (by decreasing input levels). This implies that the use of the TFP index allows for a more precise identification, with respect to the use of GAP and inputs, of the contribution of R&D investment on productivity.

Table 2 shows the evolution of TFP for the sample countries over the considered period 1981-2010. The first information to highlight is that the average level of TFP index for some countries, such as IE, NO, PT and CH, is close to the reference level. The meaning of such datum is that productivity in those countries lagged behind (20 years from 1961 to 1981) with respect to the others.

On the other side, there are some countries, such as BE, DK, DE, IT, NL and ES, for which the average TFP index is greater than 200. Such variability across countries in TFP index is a favorable element for the reliability of an inferential procedure aimed at estimating the impact of R&D investments over years at country levels, i.e. the exercise we are carrying out in this paper. By looking at the yearly trends, in terms of average percent change, the sample shows a notable variability across countries, from about 1% for UK to 4% for DK. Indeed, a deeper exploration of the yearly evolution at country level, not shown in Table 2, shows that most countries record a flat trend until 1990 (1987 for IT, NO, PT and ES) and a steady (but variable across countries) increase thereafter. Only NL and SE show constant positive tendencies along the entire period[11].

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[11] For a detailed description of the TFP series see the Deliverable 4.1 of IMPRESA project, downloadable at: http://www.impresa-project.eu/home.html

Table 2. Total factor productivity (TFP) (reference level: 1961=100).

	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland
1981	130	139	121	122	119	134	147	109
2010	263	226	330	190	222	292	215	160
Mean	194	201	208	155	167	210	188	133
St. Dev.	48.65	38.75	72.44	28.05	37.89	54.19	32.10	18.64
Aver. % Δ	2.73%	1.98%	3.88%	1.51%	2.51%	2.86%	1.88%	2.65%
	Italy	Netherlands	Norway	Portugal	Spain	Sweden	Switzerland	United Kingdom
1981	163	169	105	89	193	115	116	136
2010	358	365	164	209	386	196	218	172
Mean	227	239	131	137	270	159	139	153
St. Dev.	58.71	53.35	17.95	34.54	67.92	26.57	27.06	10.86
Aver. % Δ	2.82%	2.45%	1.41%	2.80%	2.73%	1.87%	2.03%	0.78%

Source: own elaboration on USDA data 1981-2010; the first line includes values for 1981 as a term of reference.

The flatness of TFP until 1990 might prove to be a factor consistent with the supposed role of R&D investments in inducing productivity growth over time. In fact, given that the trends of the inputs do not show flat trends, but rather decreasing ones along the entire period, it is plausible to hypothesize the attribution of the initial stability and the subsequent growth of TFP to a likely progressive growth in technical and allocation efficiency originating from research. This preliminary assessment suggests that the selected data could be considered suitable for testing the hypothesis of a relationship between R&D expenditures in agriculture and agricultural productivity. Based on available time series, in this paper we estimate the direct impact of public expenditure on R&D on TFP and, in turn, the relative RoR, by employing the most appropriate methodology, suitably tailored to the available series of data.

4. METHODOLOGY

Despite many years of academic analysis, the study of the impacts of agricultural R&D on the economy has not converged in a well-established and agreed upon methodology. Two main theoretical streamlines of economic growth support the study of economic impact of R&D, the exogenous and endogenous growth models, which in turn give rise to different methodological approaches. The differences, as well as the *pros* and *cons*, between these main approaches for the study of the economic impact of R&D are well exposed by Parente (2001), who considers the exogenous growth model the best analytical framework for the assessment of economic growth because it best describes the convergence process of countries' economies. Within the framework of the exogenous growth model for assessing the RoR, expenditures in R&D are employed as a proxy for knowledge accumulation and, therefore, treated as an exogenous capital input in the estimation process. This assumption implies that the effect of the R&D investment is supposed to persist beyond the first year, therefore affecting more than one production cycle[12]. This condition implies the use of time series analysis techniques because the focus is on assessing the long-run growth and returns. However, being aware of the limitations of the available data and the consequent impossibility of applying the best available methodology, a wide review of the recent literature, including, *inter alia,* Schimmelpfennig et al. (1999), Fan (2000), Oehmke (2004), Ali (2005), Alene et al. (2009), Alene (2010), Suphannachart (2011), Andersen (2013), Hurley et al. (2014) and Jin et al. (2016), has been carried out to identify the analytical approach that could best exploit the informational power of the available data.

These studies provide a variety of approaches and model specifications for the estimation of the impacts of agricultural research on productivity. The methodologies adopted are diverse across the reviewed works and have been likely chosen to best exploit the available data of each study. In fact, agricultural productivity is measured in GAP, Value Added, TFP and MFP, while research is measured in knowledge stock, distributed or single lags of R&D expenditure. In fact, the way research is assumed to impact productivity over time is also modelled in several ways, either by imposing a certain number of lags, based on specific assumptions

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[12] In this case, the production cycle coincides with one year.

regarding the nature of the research system mainly present in a country (basic, experimental, adaptive, extension, etc…) (Alene, 2010), or by inferring the length through information criteria of regression models, such as Adjusted R^2, AKAIKE, Likelihood ratio and other criteria (Fan et al., 2000; Alene et al., 2009). The presence of lags inevitably yields estimation issues (biases) due to multicollinearity, implying the imposition of a limit in the length of the time lag. Furthermore, research lags are not modelled according to a linear impact path, but rather designed in specific shapes accommodating the largely shared hypothesis that the impacts of R&D grow in the early years right after the implementation of the research, reach a peak and then decrease. Such non-linear impact paths are modelled in different ways in the literature, in particular as PDL (polynomial distributed lags), Gamma distribution function, triangular or trapezoidal (Sumelius, 1987; Thirtle and Bottomley, 1988; Thirtle and Bottomley, 1989; Thirtle et al., 1995; Schimmelpfennig et al., 2000; Alene, 2010).

The most accredited literature is not unanimous on the required lag length and differences depend on the underlying assumptions. In fact, in order to assess the total effects of R&D expenditures from the beginning of a research project to the complete obsolescence of the related technology, Alston et al. (2000) suggest a period of at least 50 years. Pardey and Craig (1989), instead, indicate the necessity of a lag length of at least 30 years to be able to capture the long-run impact of R&D on agricultural output. It is useful to stress, however, that such a condition is mainly found in studies in which the United States is the subject of the estimation and for which the assumption of the research activities, composed mainly of basic (relative to applied) research, is coherent with the hypothesis of long-term impacts on productivity. In Europe, however, previous studies adopted, on average, lag lengths of less than 30 years. Although the methodological approach applied in the European studies is in line with the one applied in the US studies, the best performance of the estimation models applied on Europe data is achieved with an average lag length of between 9 and 12 years and by imposing a polynomial distributed lag (PDL or Almond) structure (inverted "U"), through which a dynamic evolution (rise-peak-fall) of the effects can be accounted for (Sumelius, 1987; Thirtle and Bottomley, 1988; Thirtle and Bottomley, 1989; Rutten, 1992; Shimmelpfennig et al. (1994); Thirtle et al., 1995). Indeed, as highlighted by Shimmelpfennig et al. (1994), Piesse et al. (2010) and Pardey et al. (2018), the likely prevalence in Europe of adaptive research activities (with respect to basic research) accommodates the assumption of reduced

R&D lagged effects (with respect to the US) and, according to Piesse et al. (2010), the use of 30 year series ought to be sufficient to capture lagged effects of R&D on productivity and acceptable from a methodological perspective. It follows that the models in the literature with the characteristics we are looking for are the ones proposed by Alene et al. (2009) and Alene (2010). Such models proved to be able to manage relatively short time series and to provide for robust results by employing structured lagged variables for R&D expenditure.

Given the objectives of this paper, we intend to apply a panel analysis, opportunely specified such as to accommodate at best the available data. The model specification has the objective of estimating the effect of the R&D expenditure on TFP, through the most efficient estimator of the panel models[13].

We used a TFP (Total Factor Productivity) index as dependent variable, and R&D investments GBAORD (constant 2005 USD) (OECD) and lags, in terms of *PDL* as independent variables.

To overcome the issue of multicollinearity of R&D lags, the following polynomial distributed lag (PDL) specification of second order has been applied to R&D lag variables (GBAORD):

$$PDL = \sum_{j=0}^{J} \alpha_j (R\&D_{t-j}) \qquad (1)$$

$$\alpha_j = \beta_0 + \beta_1 j + \beta_2 j^2 \qquad (2)$$

with $j=0,1,…,J$, where J represents the maximum lag or, in other terms, the lags' length;
by substituting (2) into (1), we obtain the following formulations of the *PDL* variable:

$$PDL = \sum_{j=0}^{J} (\beta_0 + \beta_1 j + \beta_2 j^2)(R\&D_{t-j}) \qquad (3)$$

$$PDL = \beta_0 \sum_{j=0}^{J} (R\&D_{t-j}) + \beta_1 \sum_{j=0}^{J} (R\&D_{t-j})j + \beta_2 \sum_{j=0}^{J} j^2 (R\&D_{t-j}) \qquad (4)$$

To avoid crossed effects between R&D and productivity (negative α_j coefficients)[14], an end-point restriction is applied such that expenditures in years $t+1$ have zero effects on productivity in year t:

$$\alpha_{-1} = \alpha_{j+1} = 0 \qquad (5).$$

By expanding (5), the following specifications can be obtained:

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[13] To evaluate whether to employ the fix- or random- effect model.
[14] By crossed effect between R&D and productivity is meant the potential effect that TFP at time t might have on R&D at time $t+1$, that is the negative coefficients.

$\alpha_{-1}=0 \Rightarrow \beta_0+\beta_1(-1)+\beta_2(-1)^2=\beta_0-\beta_1+\beta_2=0 \Rightarrow \beta_0=\beta_1-\beta_2$ \hfill (6)

$\alpha_{J-1}=0 \Rightarrow \beta_0+\beta_1(J+1)+\beta_2(J+1)^2=\beta_0+\beta_1 J+\beta_1+\beta_2 J^2+2\beta_2 J+\beta_2 J=0.$ \hfill (7)

By substituting (6) in (7) and then (8) back in (6), the following final specifications are obtained:

$\beta_1-\beta_2+\beta_1 J+\beta_1+\beta_2 J_2+2\beta_2 J+\beta_2=0 \Rightarrow \beta_1(2+J)+\beta_2(2+J)J=0$
$\Rightarrow \beta_1=-\beta_2 J$ \hfill (8)

$\beta_0=\beta_1-\beta_2 \Rightarrow \beta_0=-\beta_2 J-\beta_2 \Rightarrow \beta_0=-\beta_2(1+J).$ \hfill (9)

The restriction implies the estimation of only β_2 and obtaining the other coefficient from the following equations (8) and (9). Once the β_2 coefficient has been obtained, the effects $\alpha_j \forall j$ and the total effects $\sum_{j=0}^{J}\alpha_j$ can be estimated.

The lag length J has been decided through the max $AdjR^2$ criterion, which makes it possible to choose that lag that maximizes the adjusted R^2 of the free-form lag structure of the estimation equations (Fan et al., 2000; Greene, 2003; Alene, et al. 2009).

Two different specifications of the panel model have been applied and controlled for heteroscedasticity:
1. TFP *level*: $TFP_{it}=\gamma_0+\gamma_0 PDL_{it}+e_{it}$, *PDL* computed on GBAORD;
2. TFP *log*: $\ln TFP_{it}=\gamma_0+\gamma_0 PDL_{it}+e_{it}$, *PDL* computed on ln(GBAORD)

where i indicates the countries and t the period between 1981-2010. Given the proposed methodology, it is expected that the sign of the *R&D* lags (calculated back from *PDL*) will be positive[15]. Random- (REff) and fix-effect (FEff) models produce estimates according to the computational formula of the random-effect and within estimator, respectively. This implies a rigid constraint on the interpretation of the results, which must be attributed to, or referred to, the panel and not to the individual countries.

Data have been tested for the presence of unit root through several tests, both as a single series and as a panel, and the results indicate that not all series and panels are stationary. Given that this result is not sufficient for co-integrating the data, a further co-integration test, namely the Pedroni (2004) test, has been applied. The results of the Pedroni test indicate that the couple of series (TFP-GBAORD) share the same stochastic trend and that such data become stationary if a linear combi-

nation of the relative variables is applied[16]. Based on this, we opted for the use of standard OLS econometric procedures, in the version of the panel model, in order to obtain super-consistent parameter estimates (Andersen et al., 2013).

Within the framework of cost-benefit analysis, an effective methodology for the evaluation of the economic impact is the computation of the rate of return of R&D investments. In particular, by referring to several studies, especially to Griliches (1964) and Davis (1981), in this paper the computation of the RoR has been carried out according to the method of the marginal internal rate of return (MIRR).

The MIRR for both TFP specifications has been computed according to the criteria adopted by Alene (2010): $\sum_{j=0}^{J}\frac{VMP_{t-j}}{(1+MIRR)^j}=1$, with $J=$"18" and $t=\{$"1981-2010"$\}$, where VMP stands for *value marginal product* of R&D. Given that the RoRs have been computed upon estimates from panel models, they are unique for all the countries. Further, different average measures are applied, namely arithmetic vs geometric, in order to control for the potential effects of the deflation of the *value* variables, namely RE, on the VMP and RoR (Davis, 1981). In fact, important differences emerge from the comparison of the RoRs computed through the mentioned techniques. However, the application of geometric averages is not possible for the variables in level form because the relative computation formula of the VMP does not involve the average of R&D[17] (but also because, by definition, the geometric average of a variable is the equivalent of the arithmetic average of the logarithmic form of the variable). Therefore, the sensitiveness of the RoR computation with respect to the geometric mean is performed only on the TFP *log* specifications.

5. RESULTS

By applying the max $AdjR^2$ criterion, 18 lags have been found for TFP specifications, implying that the variable $PDL=\sum_{j=0}^{J}j^2(R\&D_{t-j})$ is computed with $j=0,1,...,18$.

The Hausman test applied on the TFP level specifications reports an estimated $\chi^2=9.59$ and a $\rho<0.05$, revealing that the random-effect model results are more appropriate. For this reason, a further model including an autoregressive process of order 1 in the error term (AR(1)) is employed to consider likely effects of omitted

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[15] The coefficient of the variable *PDL*, namely , given the imposed shape of an inverted parabola, is expected to be negative. The corresponding lag coefficients of R&D, instead, namely , are expected to be positive.

[16] More details about the unit-root tests are available from the authors upon request.
[17] The computation of *VMP* varies according to the TFP specification used in the models: the *log* form implies the use of average values of TFP and RE, while the linear form does not.

variables unlinked to single countries (coherent with random-effect model specification). On the other hand, the Hausman test applied to TFP *log* specification reports an estimated $\chi^2=0.02$ and a $\rho<0.89$, suggesting that fix-effect model results more appropriate. However, we decided to run a REff model with AR(1) disturbances to account for missing variable bias, given that no efficiency as well as consistency would be lost. The lags imposed on the models, although computed empirically, have been double-checked by referring to the work by Piesse at al. (2010) who propose the existence of a diffusion path from the US to less developed Southern countries, passing by Northern and Southern Europe, backing the hypothesis that agricultural research in Europe is mostly adaptive rather than basic. Given this path, the lags from research to productivity in Europe may be expected to be shorter than the suggested 50 years. The empirical determination of the lags seems to confirm this hypothesis.

The variables in the TFP model specifications have been employed in the form of levels and logarithm. The results, displayed in Table 3, show the expected positive sign of the R&D estimates and high statistical significance.

Across the considered 18-year lag period, the variables on agricultural research (R&D) indicate positive and significant effects, shown in Figure 1, summing up to a total effect of 0,24 and 0,17, for the REff and REff with AR(1) specifications in level forms, and to a total elasticity of 0,10 and 0,09 for FEff and REff with AR(1) specifications in logarithmic form, respectively.[18]

By comparing the results of the different specifications of the models on TFP, interesting estimation aspects are revealed. In particular, the inclusion of the AR(1) component in the error term does not improve the regression accuracy (both R^2-within and R^2-between) as well as the estimation of the R&D effects, which, rather, turns out to be lower. The reason for this difference in the estimates (or lack of difference in R^2) might be related to the condition that both regressions include only one explanatory variable, namely R&D (in terms of *PDL*), inducing a lower impact when the AR(1) error component is considered. In this case, the relative importance of differences across countries *versus* time-related variability is null. Further, other aspects emerge from the regression performed through the FEff estimator in that it excludes the *between variation* from the estimation process. The results, shown under the column titled *Log form* in Table 3, indicate a lower performance of R&D (in terms of

Table 3. Results from TFP specifications.

TFP	Level form		Log form	
	REff	REff w/ AR(1)	FEff	REff w/ AR(1)
Constant	152.6***	169.5***	4.838***	4.908***
$R\&D_t$	0.003***	0.002***	0.002***	0.001***
$R\&D_{t-1}$	0.007***	0.005***	0.003***	0.002***
$R\&D_{t-2}$	0.009***	0.007***	0.004***	0.004***
$R\&D_{t-3}$	0.012***	0.008***	0.005***	0.004***
$R\&D_{t-4}$	0.014***	0.010***	0.006***	0.005***
$R\&D_{t-5}$	0.015***	0.011***	0.007***	0.006***
$R\&D_{t-6}$	0.017***	0.012***	0.007***	0.006***
$R\&D_{t-7}$	0.017***	0.012***	0.007***	0.007***
$R\&D_{t-8}$	0.018***	0.013***	0.008***	0.007***
$R\&D_{t-9}$	0.018***	0.013***	0.008***	0.007***
$R\&D_{t-10}$	0.018***	0.013***	0.007***	0.007***
$R\&D_{t-11}$	0.017***	0.012***	0.007***	0.007***
$R\&D_{t-12}$	0.017***	0.012***	0.007***	0.006***
$R\&D_{t-13}$	0.015***	0.011***	0.007***	0.006***
$R\&D_{t-14}$	0.014***	0.010***	0.006***	0.005***
$R\&D_{t-15}$	0.012***	0.008***	0.005***	0.004***
$R\&D_{t-16}$	0.009***	0.007***	0.004***	0.004***
$R\&D_{t-17}$	0.007***	0.005***	0.003***	0.002***
$R\&D_{t-18}$	0.003***	0.002***	0.002***	0.001***
$R\&D_{Total}$	0.24***	0.17***	0.10***	0.09***
R^2 within	0,3078	0,3078	0,6866	0,6866
R^2 between	0,0101	0,0101	0,1172	0,1172

Note: *** represent statistical significance at the 1% level. Standard error for lagged R&D coefficients has been computed via Delta method.

PDL) because the country-level effects are flattened out. However, the models run under the FEff and REff (w/o AR(1)) estimator return exactly the same results, while the inclusion of the AR(1) component lowers the elasticity estimates but does not affect the goodness-of-fit. The observed sensitiveness of the effect of R&D on productivity supports the need to include more variables that potentially might affect agricultural productivity in the long-run to better isolate the impact of R&D. In particular, we refer to other elements, especially country-specific factors, such as climatic elements, weather anomalies, private investment in research, spill overs and agricultural policy implementation. Although some of these have been tested in the models (such as climate and CAP) the obtained results were not improving. In fact, both variables were not statistically significant.[19]

[18] Each coefficient of the variable $R\&D_{t-j}$, i.e. current and lagged effects, has been computed from the original estimates of the *PDL* variables $\beta_2=-0.000182$ (z-value= -13.64) and $\beta_2=-0.000129$ (z-value = -5.24) for both RE model specifications in levels, respectively, and $\beta_2=-0.000077$ (t-value = -9.00) for FE model specification in logarithm.

[19] For climate, we used two climatic indexes, growing and cooling degree days indexes, estimated by the Joint Research Center (JRC) of the European Commission within the framework of AGRI4CAST Tool-
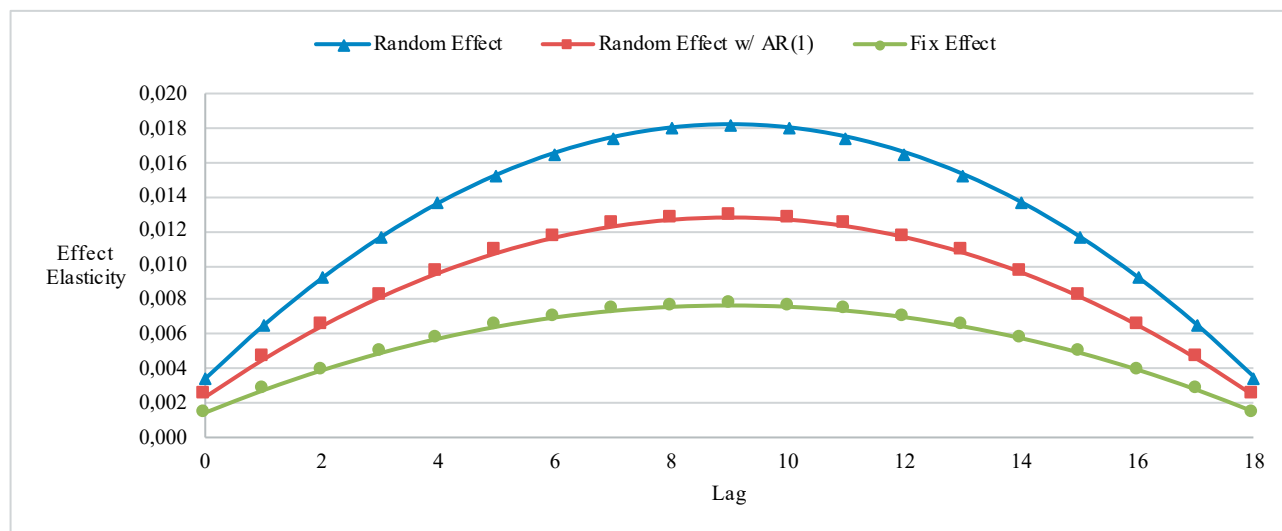
Figure 1. Distribution of single R&Dt-j effects in TFP specifications. Source: own elaboration. Note: FEff estimates are elasticities; REff estimates are marginal effects.

The estimated coefficients obtained from all specifications (both marginal effects and elasticities), beyond characterising and quantifying the relationship between R&D investments and productivity, are the fundamental elements of the assessment, via RoR, of the economic impact of R&D.

The measure of RoR is expressed as the MIRR that equates the marginal value of productivity to the unit value of research expenditure (RE). Depending on the regression results, the computed RoR for TFP specifications, shown in Table 4, follows the same variation in magnitude as the elasticity estimates.

In particular, the RoRs computed via the estimates obtained through the models employing the AR(1) component in the error term turn out to be smaller than the counterpart (w/o AR(1)).

The application of geometric means to TFP in the *log* specification yields higher returns, namely 9.13% vs 7.03% and 7.59% vs 6.58%.

This result is essentially due to a rebalancing of the average values of R&D lags. In particular, the geometric average, applied first to cross-country and then to lags, reduces the average value of the early lags and raises the values of the farther lags. Essentially, in this specific case, the geometric means flattened the R&D lags, by increasing the slope of the downward trend of the lag series. As related to the computation of the RoR, applying the geometric means to RE leads to the estimation of

a higher contribution of past R&D to the present value of agricultural production.

The values of RoR obtained by including the AR(1) component in the error term ought to be considered as the most reliable, because they account for omitted variables having potential effects on the entire sample. However, the observed variation, from 7.0% to 6.6% for arithmetic means and from 9.1% to 7.6% for geometric means, do not change the magnitude of the estimated RoR in a meaningful way.

6. DISCUSSION

The RoR on investments in agricultural research in Europe is consistently positive across different analytical methods. However, our estimates are comparatively low with respect to most findings documented in the literature for developed countries. Moreover, the results confirm that RoR computation is sensitive to the specification of the models, the method applied to measure the variables, the lag length and its shape and the territorial coverage. In fact, if compared to other works, such as Schimmelpfennig et al. (2000a) (in the closed economy case), the RoRs obtained in this paper are to be considered very low. Indeed, these results might depend on several differences between our study and those used as a comparison, including the time period, and the relative length (1973-1993, in which agricultural productivity recorded high levels of TFP growth, vs 1981-2010), and a wider coverage of countries (we included Spain and

box, specific for the agricultural sector. For CAP, given the unavailability of country level data, we applied a dichotomous variable at year 1992 as proxy for the MacSharry reform.

Table 4. Computation of the Internal Rate of Returns (IRR) for the TFP specifications.

j	Variables in level form				Variables in logarithmic form									
					Arithmetic average					Geometric average				
	α PDL	VMP	α PDL (AR1)	VMP	RE	α PDL	VMP	α PDL (AR1)	VMP	RE	α PDL	VMP	α PDL (AR1)	VMP
0	0.004	0.04	0.002	0.03	183	0.001	0.02	0.001	0.02	115	0.001	0.03	0.001	0.02
1	0.007	0.08	0.005	0.06	182	0.003	0.03	0.002	0.04	115	0.003	0.05	0.002	0.05
2	0.009	0.11	0.007	0.08	181	0.004	0.05	0.004	0.06	114	0.004	0.07	0.004	0.07
3	0.012	0.14	0.008	0.10	179	0.005	0.06	0.004	0.08	114	0.005	0.09	0.004	0.08
4	0.014	0.17	0.010	0.12	178	0.006	0.07	0.005	0.09	113	0.006	0.11	0.005	0.10
5	0.015	0.19	0.011	0.13	147	0.006	0.10	0.006	0.11	113	0.006	0.12	0.006	0.11
6	0.017	0.20	0.012	0.14	141	0.007	0.11	0.006	0.12	112	0.007	0.13	0.006	0.12
7	0.018	0.21	0.012	0.15	135	0.007	0.12	0.007	0.12	112	0.007	0.14	0.007	0.13
8	0.018	0.22	0.013	0.16	129	0.008	0.13	0.007	0.13	111	0.008	0.14	0.007	0.13
9	0.018	0.22	0.013	0.16	124	0.008	0.14	0.007	0.13	111	0.008	0.15	0.007	0.13
10	0.018	0.22	0.013	0.16	118	0.008	0.14	0.007	0.13	110	0.008	0.15	0.007	0.13
11	0.018	0.21	0.012	0.15	112	0.007	0.15	0.007	0.12	110	0.007	0.14	0.007	0.13
12	0.017	0.20	0.012	0.14	107	0.007	0.15	0.006	0.12	110	0.007	0.13	0.006	0.12
13	0.015	0.19	0.011	0.13	101	0.006	0.14	0.006	0.11	109	0.006	0.12	0.006	0.11
14	0.014	0.17	0.010	0.12	95	0.006	0.13	0.005	0.10	109	0.006	0.11	0.005	0.10
15	0.012	0.14	0.008	0.10	90	0.005	0.12	0.004	0.09	109	0.005	0.09	0.004	0.09
16	0.009	0.11	0.007	0.08	84	0.004	0.10	0.004	0.07	109	0.004	0.08	0.004	0.07
17	0.007	0.08	0.005	0.06	78	0.003	0.08	0.002	0.06	110	0.003	0.05	0.002	0.05
18	0.004	0.04	0.002	0.03	72	0.001	0.05	0.001	0.03	109	0.001	0.03	0.001	0.03
MIRR	15.21%		9.51%		7.03%			6.58%		9.13%			7.59%	

Source: own elaborations

Portugal, the economies of which were lagging behind in 1973-1993, as well as Sweden, Finland and Norway, characterised by particular climatic conditions, limited agricultural activities and intensive use of advanced technologies).

Despite this, the RoRs resulting from the analyses might be deemed reasonable when considering that most of the agricultural research carried out across the European countries has the characteristic of being adaptive, rather than basic research. In this regard it is important to highlight that, beyond the methodology and the variable measurement, the RoRs are sensitive also to both the length and the shape of the lags elapsing between R&D and agricultural productivity, as shown by the differences obtained by applying arithmetic and geometric averages. In particular, further potential contributions could come from imposing a shape of fourth-order *PDL* (or positive-valued distribution function) with a positive skew in order to impute more weight on the effects of the early lags.

The results presented in this paper may suffer from potential limitations stemming from available data, namely GBAORD, which are a proxy of actual expendi-ture, and from the omission of unavailable information potential used as covariates. In fact, as suggested by the difference in the results due to omitted variables, despite the general goodness and robustness of the estimations, model specifications are susceptible to improvements by including and controlling for more variables, especially those likely affecting agricultural productivity in direct ways unlinked to own-country agricultural research, such as evolution of farm structure, spill overs, weather, trade flow and agricultural policy.

In particular, including aspects regarding the CAP reforms and accounting for spill overs as well as climate evolution could potentially modify the results. Further, the availability of data on private expenditures on agricultural R&D and the use of longer and more complete time series might have furtherly increased the robustness of the results. The consideration of these variables in this paper was explored, but the results were not satisfactory, most likely due to limitations in data availability. In any case, even if data had been available their use would also have required a reformulation of the analytical models in a consistent way.

In perspective, if data become available, different strategies may be envisaged to improve this study. The correctness of the model specifications and, hence, the robustness of the results would largely benefit from a wider analytical approach that is able to consider the modern transformations occurring in the European agricultural sector. We refer, in particular, to the growing interest of research, including agricultural research, and policies, especially the CAP, towards the development of technologies, practices and measures devoted to aims other than productivity, such as improving environmental protection, food safety and climate change mitigation.

However, the impact of these variables is not straightforward. For example, the CAP, on the one hand promotes innovation measures accelerating the transfer of research results to farmers, and on the other hand includes measures aimed at improving the sustainability of agricultural production processes but that indirectly might induce the effects of moderating the productivity. As a result, the direction of this impact is an empirical issue and may be correctly accounted for only by disentangling the effects of different measures.

Moreover, agricultural productivity itself as a focus of analysis ought to be revisited. Indeed, it is not only productivity, by the means of research, that brings about benefits to society. Other measures able to contemplate the effects of research on side aspects related to the agricultural production processes could be investigated, such as the societal value of the provision of public goods or the environmental protection, such that even the relative RoR would be much more representative of broader research efforts.

All these aspects and dynamics require a deeper analysis and could be the subject of further investigations in the years to come, especially as they would need better data than those currently available.

7. CONCLUSIONS

In this paper we analyse the impact of public R&D on agricultural productivity at the aggregate level, by using data from 16 countries, that can be considered as representative, in aggregated terms, of the European agricultural sector. Based on this, we estimate the RoR of public research expenditure in Europe. Our results add updated empirical information on the topic, by widening both the period of analysis and the territorial coverage at the European level as compared to existing studies.

The results corroborate the hypothesis that, on average, research expenditure has a generally positive impact on productivity, which yields a relevant RoR. Our esti-

mates show returns of public R&D investments on agricultural productivity of between 6.5% and 15.2%, varying according to model specifications and computation techniques. These results are consistent with other estimates from the literature, though lower than results from the US. The time lags are shorter than reported by most of the US literature.

The general policy message from this paper is that the return on public research expenditure justifies investments in agricultural research, especially considering the low return from alternative investments in the current stage of the economic cycle. At the same time, the level and variability of return according to different estimation methods and different countries/sectors hints at the need for a careful evaluation of expenditures at the stage of programme/project funding. This would require a more detailed *ex-ante* evaluation of expected returns, but also attention to the widest range of priorities by policies (beyond productivity), more attention to targeting of expenditure as well as greater attention to factors that enable fast and effective research impact. This is indeed the route taken by current R&D funding policies at the European level.

The analysis has limitations related to data availability, especially concerning research expenditure. The main limitations concern the length of the available time series and the level of standardisation (comparability over time and space) of expenditure data. This also reflects on the methodological approach used, as the study was carried out by employing the most suitable methodology able to accommodate both the quality and availability of panel data.

In spite of the wide room for improvement, this work should be useful as a reference basis for further studies, especially for evaluating the impact of private R&D investments, the role of spill-overs as well as the effects of CAP reforms on agricultural productivity, both at the country and European levels. An additional pathway for further research is to take into account the diversity characterising the research policies of different European countries. A satisfactory exploration of these routes will require consistent improvements in the availability of methodologies and datasets, with a strong priority for the latter.

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