Do collaborations enhance the high quality output of scientific institutions? Evidence from the Italian Research Assessment (2001-2003)

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Abstract

The aim of this paper is to analyze the effects of research collaborations on the scientific output of academic institutions, drawing on data from the 2001-2003 Italian Research Assessment. We measure the scientific performance of a research unit as the number of publications that received excellent, good, and acceptable grades in the evaluation process. Using a Negative Binomial model for count data, scientific quality indicators are regressed on institution-specific variables and on the strength of research collaboration, proxied by the number of coauthors per researcher, the share of coauthors affiliated to other research organizations, and the number of visiting researchers. The results highlight the beneficial role for scientific quality of formal co-authorships between researchers from different institutions and of the informal knowledge exchanges allowed by visiting periods.

1 Introduction

In recent years, scientific productivity has become one of the most important issues for economic policy, giving rise to a strand of studies by economists and other social science scholars. Central to this issue is the increasing trend in scientific collaborations that can be spotted in the statistics on international academic publications since the second half of the Eighties in all fields of research and at different levels, both between individuals and between institutions (Hack and Zaleski, 1991;

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Durden and Perri, 1995; Rosenblat and Möbius 2004, Goyal et al. 2006). As a matter of fact, the direct co-operation between two or more researchers, which often has taken the form of coauthorship, has dramatically increased[1] (Laband and Tollison 2000, Adams et al. 2005, Ziman 2000, Gibbons et al. 1994, Slaughter and Leslie 1997), and there has been also a huge rise in co-operation between departments within the same institutions, between institutions[2] and between countries (Katz and Martin, 1997; Kalaizidakis et all. 2004; Adams et all. 2005). Several possible explanations have been advanced for the growing incidence of academic collaboration: the explosion of knowledge which has increased the gains from specialization (McDowell and Melvin, 1983); the reduction in communication costs brought about by technical change (Rosenblat and Möbius, 2004); the "mentor" motive and changed preferences for collaboration (Laband and Piette, 1995; Bozeman and Corley, 2004). However, such a rise in scientific collaborations is also the effect of policies aimed at increasing them. Indeed, most governments have launched initiatives, such as bringing researchers together in new and large centers of excellence, or increasing the level of international collaboration[3], with the aim of developing collaborations among individual researchers, among departments and universities. Implicit in these policies is the belief that an higher level of collaboration will boost the research productivity both at the individual and at the institutional level. However, the existing literature has not found a univocal effect of collaborations on scientific productivity. It is not clear how strong this relationship is and what are the relevant channels.

The aim of this paper is to analyze the effects of research collaborations on the scientific output at the institutional level. In particular, in this paper we estimate, through an econometric analysis, the effect of scientific collaborations, which arise within the same university and between different universities, on the production of high quality research. Our focus on the quality aspect is based on the consideration that, although the quantitative evaluation of scientific output deserves some attention, quality is the most important characteristic of scientific productivity, because the ultimate impact of any research work on the advancement of scientific knowledge cannot be fully captured by a quantitative measure.

In order to measure high quality research, we use data drawn from the Italian Research Assessment in the period 2001-2003, which is the first systematic evaluation of the academic research performances in Italy. Hence, we measure the quality of research by using the evaluation of articles given by panels of experts,

[1]Laband and Tollison (2000) stress that even in a social science field such as economics, coauthorship has increased dramatically since the early 1950s. The same increasing trend has been observed in other disciplines, such as biology.

[2]Analysing data on U.S. universities, Adams et al. (2005) show an increasing trend in the formal collaboration among scientists in 12 scientific fields during the period 1981-1999.

[3]See on this point Katz and Martin (1997) and Bonaccorsi and Daraio (2005).

that have classified all scientific outputs presented by Italian universities according to several grades of quality, ranging from excellent to limited grade. In the literature other measures of research quality such as citation counts, indexes based on the number of pages and the quality of the journal wherein articles are published, are often used (Laband and Piette, 1995; Hollis, 2001). Nevertheless, we prefer the evaluation given by the research assessment, since this way of classifying academic publications has the advantage of the uses of all the available information (citations, impact factor, number of pages etc.) by competent referees who can make a more precise evaluation than metric-based indicators (on this point see also Clerides et al. 2009). More particularly, we estimate a model for count data whose dependent variable is the scientific output of a research unit differentiated according to the quality grades. We focus in particular on products defined "excellent" and "good", since both grades capture the high quality research. However, in order to allow a better interpretation of the econometric results, we estimate the same model on data that refer to the grade "acceptable" products, which corresponds to the third grade of the ranking. Indeed, we expect the factors that influence the production of high quality publications should have an opposite effect on those of the lower quality.

Since our focus is on the effects of scientific collaborations on the research output of an institution, the unit of research is defined as the pool of researchers who belong to the same academic organization and to similar fields of research. The available data concern 102 public and private universities and research organizations in 20 fields, including basic, applied, social, and human sciences. Hence, the data refer to the whole range of academic institutions and fields, providing a comprehensive picture of Italian science.

In order to capture the effect of scientific collaborations, we include among the explanatory variables three indicators of intellectual collaboration: the number of authors per researcher, which measures the effects of collaboration among individuals without distinguishing those authors who belong to the same institution and those who belong to different universities; the ratio between the authors affiliated to other academic institutions and the total number of authors, which captures the effects of external collaborations; and the number of researchers in international mobility, which captures the effects of international collaborations, including informal ones. The whole set of intellectual collaboration indicators can give a comprehensive picture of how and whether scientific collaborations that arise within a scientific institution, between different institutions and between countries boost the productivity of scientific organizations.

The econometric model also takes into account other factors that may affect the scientific output of an institution, such as its age, the resources it has invested in the research activity, the average age of the affiliated researchers, the number of its PhD students, the ratio between research and administrative staff.

The results are particularly interesting. First of all, we find that collaborations per se are not significantly associated to high-quality research. What really improves scientific productivity is the interaction with scholars who do not work in the same university/institute. This effect is even greater when interactions occur among researchers of different countries. According to regression results, such positive effects of external interactions are limited to the publications that received higher quality grades, and those effects can turn negative when publications of lower grades are considered. Interestingly, coauthorship as such increases the probability of producing more publications, but this effect is not significant and even negative in the case of high quality publications. Moreover, we find a strong positive association between international mobility and the probability of excellent publications. This result brings support to the view that, in order to improve the quality of its publications, a scientific organization has to encourage interactions with scientists from other institutions.

The paper is structured as follows. Section 2 reviews the main empirical and theoretical results achieved by the literature on scientific collaboration. Section 3 presents an empirical model of scientific production and describes the data and the empirical strategy. The results are in Section 4, while Section 5 concludes.

2 Effects of intellectual collaboration on scientific output: the previous literature

The empirical literature on the effects of collaborations on scientific product does not reach univocal results. Often results change according to the manner in which academic performance is measured, to the variable used to capture the intellectual collaboration and, finally, to the level at which the analysis is carried out, i.e. if the research unit is an individual or an institution. As regards to the measure of the academic performance, the major difference is between the quantity and the quality aspect of the scientific production. In fact, results change according to the way in which academic performance is measured, since the quality of research seems to be more influenced by scientific collaborations. The whole picture is further complicated by the fact that each one of these dimensions of research output can be measured in a different way. De Solla Price and Beaver (1966) by measuring academic performance of 592 scientists of different fields with the total number of publications, found that "there is a positive correlation between productivity and the amount of collaboration of the authors" (P. 1014). Zuckerman's study (1967) of 41 Nobel laureates, by using a similar measure of academic performance, showed that Nobel prize winners published more and were more apt to collaborate than a matched sample of scientists. Durden and Perri (1995) by using both total articles and per capita articles as a measure of academic performance, found that coauthorship enhances the productivity of a single researcher in economics. Laundry et al. (1996) by using cross-sectional data of individual researchers in different fields, found that higher rates of coauthorship are correlated with higher numbers of articles published. However, McDowell and Smith (1992), who analyzed individual scientists active in several fields, found no evidence that coauthorship increased the number of articles per scholar when total articles were discounted by the number of coauthors. On the contrary, using a panel of individual researchers in Economics, Hollis (2001) found that when academic performance is discounted by the number of authors, coauthorship is negatively related to the scientific productivity. To explain this result, Hollis suggests that the quality of research in case of collaborations is higher, and this can explain the negative relation that he find between the quantity of output and collaboration, since the "easy papers" are made by single researcher. A similar argument is followed by Rosenblat and Möbius (2004). The authors show that the reduction in communication costs has increased collaborations between distant agents, but at the same time it has reduced the collaboration between individuals with different characteristics. Lower communication costs, indeed, enable researchers to be more selective in choosing their partners, and it often turns out that good researchers are better off collaborating with similarly good researchers. The expected effect could be an increase in the quality of matchings and in the collaborations of highly talented researchers, but at the same time a reduction in the number of collaborations and in the productivity of the less talented individuals. As a consequence, there can be an increase in the production of high quality science, but also an increase in polarization that may have detrimental effects on total productivity. The polarization effect is also clear in the results found by Pravdic and Oliuic-Vukovic (1986), who analyzed collaborative patters in chemistry at both individual and group level. The authors found that the effect of collaborations on scientific output depends upon the type of links, since collaboration with high-productivity scientists tends to increase productivity, while collaboration with low-productivity scientists generally decreases it. Hence they conclude that co-authorship may increase the quality of research only if it gives rise to better matching, otherwise it can be detrimental also for the quality aspect. Finally, Laband and Tollison (2000) by relying on information drawn from the JPE submission and acceptance lists for the 1982-1986 period, provide empirical evidence that coauthored scientific papers are more likely to be accepted for publication on JPE than the sole-authored papers. They interpreted this result as a confirm that the gains from co-authorship occur, at least partially, in the form of higher-quality manuscripts.

One implication of the above results is that if the positive effect of collaborations on quality is obtained at the expense of the quantitative aspect of scientific output, the question arises as to what is the most appropriate goal from a policy-making point of view. The picture is even more complicated by the fact that a policy aimed at increasing scientific collaborations should consider also which types of collaborations are really effective for increasing research productivity, since not all of them are beneficial.

All the papers discussed so far analyze the effects of scientific collaborations at a level of a single researcher. However, in order to better understand the whole picture, we have to consider also what happen at institutional level. Indeed, most policies set up by governments, aimed at fostering collaborations, are at institutional level, rather than at individual level. On this aspect the empirical literature is less wide and overlaps, at least partially, with the question of "the departmental effect" (Cole and Cole, 1970, Allison and Long, 1990, and Carayol and Matt, 2006). Adams et al. (2005) is among the few papers that analyzed the effects of collaborations on the scientific productivity of an institution. By using panel data on scientific papers written in 110 top U.S. research universities, the authors found that universities that collaborate more with foreign institutions produce fewer papers, when these latter are "fractionated" to take into account of the estimated proportion that a university contribute to. On the other hand, collaboration with foreign institutions increases the total quality of scientific output, when this is measured by total citations, "so that a trade off of fewer papers in return for larger overall scientific influence may be taking place" (p.261). Sutter and Kocher (2004), by analyzing the pattern of coautorship at institutional level of U.S. universities, found evidence that a majority of U.S. universities produces more coauthored than single authored papers in top journals. These authors distinguish among collaborations which occur within the same institution and those between different institutions, and they found that although collaborations within the same institution are still important, the external ones allow lower ranking universities to link with high ranking universities, thereby increasing the quality of their research.

Kalaizidakis et al. (2004) used data from a survey on European economics departments to find strong evidence that collaborations with North-American universities have a positive and significant effect on the publication performance of universities. This is true both when output is measured by total articles and when it is measured by per capita articles. This paper is very interesting for our aim since they use an indicator of international collaborations very near to one we have adopted: the visiting periods and training activity undertaken by European economists in North-America. In fact, so far collaboration has been simply equated with coauthored papers, but there are different forms of collaborations, informal and formal, such as visiting periods, institutional participations to same research projects, or even only comments informally provided by colleagues, that occur very often among scientists. The effects of these different type of collaborations deserve attention since they could be very important (see on this point Laband and Tollison 2000). Finally, Ramos et al. (2006) by analyzing the performance of Spanish universities in economics and business, found that coauthorships have no significant effect on scientific production, when this latter is measured by articles weighted by the number of authors, but international collaborations have always a positive and a significant effect on scientific productivity. This result is very interesting since it is similar to that obtained by Kalaizidakis et al. (2004) and, as we will see later on, by our paper. An indirect evidence of the importance of international relations comes also from the paper of Bauwens et al. (2008), who with a cross-country analysis found that a good English proficiency has a positive and fairly strong effect on the research performance of a country. This result confirms the importance of international relations since a good English proficiency implies also a greater ability of embarking on international collaborations.

3 The empirical model

In modeling the research output of an academic unit, we assume that the research output depends on the size of the research personnel, on other inputs such as physical capital and academic staff, and on some unit- and/or organization-specific characteristics. The research units on which we focus our study are aggregates of departments which share similar fields of research and belong to the same university. In addition, we assume that the individual abilities are uniformly distributed within departments and therefore researchers are endowed with similar scientific talent. Therefore the reduced form equation for the research output can be defined as follows:

$$O = B(z)F\left[A(x)R, K\right] \tag{1}$$

where O is the scientific output, measured by the number of articles that received a certain quality grade (excellent, good, or acceptable) by a panel of referees, R is the number of researchers in a unit, K is a vector of the services from other inputs, such as physical capital and administrative staff measured at level of the academic organization, $A(x)$ represents a sort of labour-augmenting technological change related to variables (x), which influence the productivity of researchers. Among these are the average researchers' age and other variables that capture the intensity of the scientific collaborations, such as the number of coauthors, the percentage of coauthorships with external authors, and the visiting periods in foreign universities. The latter variables are measured at the unit level. The term $B(z)$ synthesizes the effects of some other university/department characteristics that modify the efficiency of all inputs. These are approximated by variables such as the reputation of the university (captured by its age) and the propensity of the unit to perform research activities, captured by the presence of PhD students.

3.1 Defining research units

We rely on data from the Italian Three-Year Research Assessment, which is the first systematic evaluation of the research outputs of Italian universities and research organizations. The assessment has been performed between February and December 2005 under the responsibility of a specialized committee, the Comitato di Indirizzo per la Valutazione della Ricerca (CIVR). The CIVR dataset, which is also the main data source for this paper[4], provides information on 645 research units localized in Italy, hosted by 102 research institutions and working in 20 research fields. The fields covered by the dataset include 14 main fields and 6 special fields[5]. Units defined according to the CIVR dataset are, roughly speaking, aggregates of departments who belong to the same university. For instance, the "Economics and Statistics unit" at a certain university includes researchers affiliated to departments as different as Economics, Business, and Statistics. In a sense, this definition of scientific units goes beyond the artificial boundaries set by university bureaucracies. We believe that this definition of a research unit is more suitable than a definition given on mere bureaucratic grounds, since scientists that belong to the same university and to the same field are exposed to the same set of organization-specific opportunities and constraints. Our definition allows to take care of this aspect of Italian university system and to assess the role of the "institutional distance" between units as a determinant of the cross-unit variance in academic performances.

3.2 The quality of the scientific output

The CIVR data provide interesting measures of scientific quality, as outcomes of the research assessment exercise. In a nutshell, the evaluation process worked as follows. CIVR invited each research institution to submit a number of research products, among those published during the 2001-2003 period, to panels of experts nominated by CIVR for each field. As a rule, each participating institution had to submit a number of research products equal to half the number of full-time equivalent (FTE) tenured researchers. The assessment therefore concerned a subset of the overall scientific production of academic units, namely the works that

[4]Data from additional sources such as the Italian Institute of Statistics, the Italian Ministry of University and Research and the universities' webpages, have also been used in order to account for university specific characteristics sources of heterogeneity among scientific teams.

[5]See Appendix.

universities/institutes wished to be evaluated upon. In turn, each panel appointed two referees for each publication, and the referees were asked to rate the products according to four grades: excellent; good; acceptable; limited. The referees were invited to express a motivated evaluation of each publication also taking into account objective information, such as citation statistics and the impact factor of scientific journals.

Since our aim is to uncover the effects of inter-institution collaborations on research output quality, we do not analyze data on the lower quality grade (limited) nor those on publications left unsubmitted to the CIVR panels. In other terms, we study the research outputs that the academic organization themselves considered as their best outputs. If unit managers were rational enough, they only submitted the best scientific products, which in their view were more likely to be awarded 'excellent' or 'good' grades. In a way, the unit members themselves considered the set of publications submitted by a unit to the CIVR committee as representative of their best scientific ability. The scientific productivity of a research unit is proxied by the number of its research products of quality grades Excellent and Good. We also estimate the model on data of Acceptable publications because the results provide some useful information on the interpretation of the results concerning excellent and good publications, too.[6]

The use of indicators based on subjective referee evaluations of scientific productivity is a distinctive feature of our econometric exercise and, as such, it deserves some comments. Up to now, no fully satisfying measure of knowledge relevance has been put forward and accepted in the scientific community. Most works in the economics of science make use of objective measures, such as citation counts, the impact factor, and the number of published papers. However, the shortcomings of citations as a measure of research productivity are well documented (Clerides et al. 2009, Coupe et al. 2009). Among recent critical studies of metric-based indicators, Oswald (2007) finds that the best article in a good-to-medium quality Economics journal routinely has a much greater citations impact than the 'poor' articles published in more famous journals. Also, citations may be biased in favor of survey articles and publications by US-based scholars. Coupe et al. (2009) show that leading papers of the European Economic Review between 1975 and 1997 received more citations than average, even though the papers were published in random order. Medoff (2003) notes that citations measure the impact of a publication, rather than its innovativeness.

Referee-based evaluation of scientific productivity, which is also at the core of the British Research Assessment Exercise (RAE), can overcome most of the shortcomings of the metric-based assessment of research quality because, although

[6]The distribution of products across grades in the CIVR dataset is the following: 30% excellent, 46% good, 19% acceptable, 5% limited.

referees usually take account of citation counts and journals' impact factor, at the same time they use further qualitative information to build their evaluation. Although, everybody wold agree that the honest referee can do a better job than a computer software, peer review has been criticized for its purported biases against new universities and in favor of universities with faculties serving on the evaluation panels. However, a recent work by Clerides et al. (2009) supports the use of subjective indicators of scientific output by showing that the biases of the RAE ratings in Economics disappear after controlling for research quality, measured by independent rankings between Economics departments. In the case of the Italian research assessment, the general opinion over the quality of evaluations was very favorable, and no critical studies of this exercise can be recorded up to now. Hence, we think that the CIVR indicators are not affected by the above mentioned biases. Another reason to prefer peer review with respect to metric-based indicators is that metric-based indicators fare poorly in the evaluation of the output in those fields, such as Literature, Law or History, where English is not commonly used and monographs are an important outlet for research dissemination.

3.3 Inputs to scientific production

The main input to scientific research is the human capital of the academic personnel, which we measure by means of the full-time equivalent (FTE) number of researchers, averaged over 2001-2003. In principle, another important inputs would be the amount of R&D funds available to the unit, but that is jointly determined with output: ceteris paribus, units with an above average number of high-quality products are also those which have obtained an above average amount of research funds awarded by means of tenders during the period of interest. Therefore, we focus on a human capital-intensive model of scientific production, i.e. one wherein the effort and skills of researchers are the main drivers of scientific production. In the econometric model, we take account of other inputs to research: the ratio of the number of non-research personnel on the number of researchers in the institution. As made clear by Eq. 1, input efficiency in knowledge production depends also on several features which characterize each university/department and the environment of research, contained in $B(z)$ term, and variables that affect directly the efficiency of labour, contained in the term $A(x)$. Variables z in the term $B(z)$ are: the age of the university given by 2004 minus the birth year, collected from their webpages and the number of PhD and post-doctoral students per FTE researcher of each department. The variables contained in the term $A(x)$ are: the average age of department researchers and the scientific collaboration variables.

3.4 Scientific collaboration indicators

Hereby we have selected three proxies of intellectual collaboration: the average number of coauthors per researcher, the share of co-authorships between researchers affiliated to different institutions out of the overall number of co-authors, and the turnover of international visiting scholars. Let us describe these variables in greater detail.

The first indicator is given by the ratio between number of authors of the publications submitted by a unit and the number of FTE researchers affiliated to that unit in the period 2001-2003. Previous papers, such as Laband and Piette (1995), Mixon (1997) and Medoff (2003), have used simple dummies to capture whether publications were coauthored by more than two or three scholars.

The strength of external collaborations is measured by the ratio between the number of external authors and the total number of authors (affiliated and non-affiliated) of the products submitted by the institution in a field. This variable sheds light on quite an important aspect of academic collaboration. Indeed, the effectiveness of social interactions in science may depend on whether coauthorships involve systematic face-to-face contacts, or long-distance communication. In particular, external co-authorships entail low communication and coordination costs; yet the quality of matching between co-authors finds a ceiling in the maximum quality of the team members, that in many teams is likely to be low in the case of small research units.

A broader measure of social interaction is the turnover of international visiting scholars (incoming and outcoming) per FTE researcher, during the 2001-2003 period. The numerator includes affiliated researchers who have visited foreign research units, as well as foreign researchers hosted by Italian institutions, for at least three months. This is a measure of openness to the international exchange of knowledge, motivated by collaborations that may also be informal, and characterized by face-to-face interaction, despite being entertained with researchers from other institutes. This variable is very important since it captures the effects of international spillovers on scientific output. According to several authors (Bauwens et al. 2008, Kalaizidakis et al. 2004, Ramos et al. 2006), such international spillovers are very effective on the research productivity of European universities, especially when international interactions occur with North-American universities.[7]

If the quality of matching is the key driver of scientific excellence, external co-authorships and international mobility are going to effectively stimulate productivity. If instead face-to-face interaction is the best route to top-quality research, external co-autorships should display negative correlation with the high-quality

[7]Unfortunately, we have no information on the countries where visiting periods have been spent.

scientific output, while a positive impact is expected from international mobility. At the same time, we are aware that there may be diminishing returns with respect to the size of the collaboration network. This may occur if the marginal cost of communicating with distant co-authors is increasing; also, if more unit members go abroad as visiting scholars, the size of the unit and the strength of within-unit interactions is effectively reduced.

Another qualitative characteristic of departments is the average age of their researchers.[8] We consider this variable to take into account both researchers' human capital and organizational aspects of departments. Actually, when a single scientist is considered, there is some evidence that productivity declines with age (Levin and Stephan, 1991), since the level of investment declines when scientists approach the date of retirement. However, at level of department, the researchers' average age depends also the relative weight of different generations of scientists, which has a strong impact on the organization of research activity. Within an institute, for example, experienced scientists might compensate their individual decline with a well organized activity of training of youngsters and of collecting funds, so that productivity at department level is not reduced (on this point see Bonaccorsi and Daraio, 2003).

Summary statistics for the selected variables are reported in Table 4.1.2, for the whole sample and for two macro-fields. Science includes 11 fields: Mathematics, Physics, Chemistry, Geology, Biology, Medicine, Agriculture, Engineering, Electronics, Computing, Nano technologies, Aerospace. The second one, Social Science, includes 5 fields: Literature and Arts, History, Philosophy and Psychology, Law, Economics and Statistics, Political and Social Sciences.

4 Econometric analysis

In the econometric literature on the economics of science, the Poisson regression model is the reference model whenever the productivity of research is measured by counts and many observations of the variable have null value (as in Zucker et al. 2006, Bauwens et al. 2008). However, this model assumes that the mean and the variance of the dependent variable are equal. This assumption does not find support in our dataset where the standard deviation of the publication counts is larger than its mean (see Table 1). This case is better handled by means of a Negative Binomial regression model, and this is the approach that we follow.

Let $y_{i,k}^{q}$ be the number of publications of quality q by unit $i = 1, ..., O$ in field $k = 1, ..., 20$, where $O(k)$ is the number of units active in the field k. Assume

[8] We obtained these data for each group of researchers in a field/institution from the Italian Ministry of University and Research.

that the probability distribution of the number of publications, conditional on the characteristics of the research unit is a Negative Binomial, with expected value

$$\mu_{i,k} \equiv E(y^q_{i,k}/x_{i,k}) = \exp(x_{i,k}\beta_q) \tag{2}$$

and variance equal to $\mu_{i,k} + \alpha\mu^2_{i,k}$. The Negative Binomial regression model allows for over-dispersion, which is the case when $\alpha > 0$. If $\alpha = 0$, then the Poisson is the appropriate distribution. Following the model of scientific production previously introduced, we specify Eq. 1 as a Cobb-Douglas, meaning that we take the natural logarithms of the regressors $x_{i,k}$. This vector also includes field-specific dummy variables that account for heterogeneity in the scientific production process across disciplines, which is not captured by other variables. Accordingly, the estimated parameters can be directly interpreted as elasticities.

One important issue concerns the causal interpretation of the estimated parameters. Indeed, most of our explanatory variables are measured in the same period as scientific productivity. Hence one can be worried about endogeneity with respect to the number of publications, but we are confident that most of our variables are not affected by such problems. Indeed, the number of researchers is a stock variable whose value is the outcome of national competitions held before 2001-2003. The proxies for coauthorship take values determined by the choice of coauthors that is usually made at the outset of a research program, hence they cannot be considered as endogenous. The age variables are exogenous for obvious reasons. Finally, while PhD students can be seen as one of the outputs of the research process - a sort of "intergenerational research output" (Adams and Griliches 2000), the PhD variable rescales the number of PhD and post-docs by the number of FTE researchers, which is strongly correlated with the level of research funds (0.84 in our sample). Thus the variance of PhD students across units is mostly due to organizational and environmental differences.

The variable which is most likely affected by endogeneity problems is the number of researchers in international mobility. Indeed, units that are more productive than average are also those better able to invite prestigious scholars, to have their fellows invited in top quality research centers, and to collect enough funds to finance long-term stays abroad. We have therefore decided to instrument the number of researchers in international mobility and to use a two-stage estimation procedure. In the first stage, we regress the number of researchers in international mobility on the exogenous explanatory variables and some instruments, to be described in a while. Along with the other exogenous regressors, the predicted values from the first stage are used in the second stage as an explanatory variable in the Negative Binomial model (Eq. 2), which is estimated via maximum likelihood. The second stage standard errors have been have calculated by means of a bootstrapping method, as in Petrin and Train (2003). Such a two-stage procedure is implemented on the whole sample, including all 20 fields, as well as on the two field aggregates previously defined: Science and Social Sciences.

As instruments, we have chosen three variables: the number of undergraduate students in international mobility (i.e. who participate to such programs as Erasmus), the amount of funds devoted to the international mobility of the students (both variables are based on data from the Ministry of University and Research), and the per capita value added of the province where the research institution is localized, as of 1998, drawn from the website of the Italian Institute of Statistics (Istat).

The international mobility of undergrads and researchers are likely correlated: for instance, students can exploit the international contacts of their professors. At the same time, there is no reason to expect correlation with the error term of Eq. (2), since more students involved in international exchange programs would not lead to better scientific performances of the research units. As to the province-level income differentials, we believe they affect the research quality only indirectly. For instance, cultural factors correlated with per-capita income may shape the internal organization of academic institutes in such a way as to restrain the international mobility of Southern researchers, without necessarily affecting their intrinsic scientific ability.

4.1 Results

Table 2 reports the coefficients of the Negative Binomial model (Eq. 2) as estimated on the whole sample, whereas the results concerning the Science and Social Science fields are respectively in Tables 3 and 4. The t statistics are provided along with the point estimates. The coefficients for field-specific dummies and the results of the first stage are omitted for the sake of saving space.

Before giving the detailed results, a couple of remarks are in order. First, the goodness-of-fit performance of the models indicates that the whole econometric exercise is able to capture the main features of the productivity of the Italian scientific units, as previously defined. The pseudo-R^2 statistics display values between 0.22 and 0.35, that is, moderately high values for a cross-sectional study. Most of the estimated parameters display high t statistics. Second, in most cases the likelihood-ratio test suggests rejection of the null of $\alpha = 0$ (i.e. equality of mean and variance of the dependent variable), providing an ex-post justification for the use of the Negative Binomial model instead of the simpler Poisson model.

The regression results confirm the importance of human capital inputs. Indeed, the parameters of the number of researchers are always significant and positive, with rather high elasticities. In particular, this effect is stronger for excellent than for acceptable publications. Hence, it seems that larger units are likely to produce a larger number high quality publications. This picture is shared by the Science fields, but in the case of Social Science we do observe similar parameters across quality grades. The balance between non-research personnel and the number of scientists has, in our estimates, positive effects on the production of excellent and good publications and negative in the case of acceptable publications, hence the size of the administrative staff per researcher is positively correlated with the quality of the research output. This result is quite intuitive, since more administrative staff implies also more personnel for laboratory equipment and more administrative, organizational and logistic assistance for research activity. The next subsections provide a detailed description of the results concerning the role of scientific interactions and of the context variables.

4.1.1 Effects of scientific collaborations

Let us turn to the proxies of scientific collaboration, namely the number of coauthors per researcher, the share of co-authorships with scholars affiliated to the other research centers, and the turnover of international visiting scholars.

A first glance at the results reported in Table 2 shows that broader interactions among researchers significantly affect the number of publications of all quality grades. Increasing the number of collaborators allows the production of more publications but at expense of their quality. Indeed, the estimated parameters of the variable authors per researcher are positive, but their value decreases along quality grades. In this respect, our estimates give interesting results. Indeed, broader interactions with other research institutions increase the probability of producing excellent publications and reduce the size of the lower quality output. More precisely, the reported coefficients imply that units with twice the share of external coauthors increase the probability of producing excellent publications by 16.89%, while the number of good and acceptable publications decrease, respectively, by about 66% and 153%. Hence, high quality research greatly benefits from interactions with colleagues affiliated to other units. The last result is reinforced by those concerning the turnover of international scholars, which is positively associated only with excellent publications. A one percent increase in the indicator of international mobility increases the probability of excellent products by 1.2291, while the same elasticity is positive but not significant in the case of good publications, negative (-1.2503) and statistically significant in the case of acceptable publications.

Splitting the sample into more homogeneous groups confirms the effectiveness of academic interactions. In the Science fields (Table 3), the coefficients and elasticities with respect to the number of authors are quite comparable with the whole sample ones, while the elasticities with respect to the share of external coauthors and to international mobility are larger (in absolute value) than in the whole sample, meaning that the benefits of contacts with other academic organizations are particularly sizable in the Science fields. More specifically, the elasticities with respect to the number of authors are .2691 (good publications), and .5748 (acceptable publications), but not significant for excellent products. Doubling the share of external coauthors yields 67% more excellent publications, a 55% reduction in the number of good publications, and a 159% drop in acceptable products. As to international mobility, the elasticities are, respectively 1.8068 (significant), -.0826 (not significant), and -1.6425 (significant).

Finally, analyzing the Social Science subsample reveals that, while intellectual collaborations retain their importance as determinants of scientific excellence, the effects of the number of coauthors and of the turnover of international scholars in disciplines such as Literature, Law, Economics and Statistics are milder than in the whole sample. The elasticities in Table 4 reveal that ceteris paribus, a unit with twice the number of coauthors enjoys 8.53% more excellent publications (not significant), and 38.83% more acceptable ones; doubling the share of external coauthors yields a 175% increase in excellent and a 162% decrease in acceptable product; the elasticities with respect to international mobility are respectively .7785 (excellent) and -.6610 (acceptable).

4.1.2 Context-specific variables

The coefficients associated to the researchers average age display statistical significance only when we break down the whole sample into the Science and Social Science fields. In Social Science, units with younger researchers have larger productivity with respect to excellent products, the estimated parameter is significant and shows quite a high elasticity (2.4364), and similarly for good products, while in the acceptable products equation it is negative (even if in these two cases the parameters are not significant). In Science, the researchers average age shows a positive parameter in excellent product and in acceptable product, but only in this case is significant. We interpret these results as evidence that in Social Science younger researchers increase the quality of research, while in Science, older researchers seem to play an essential role. The reason why Science teams with older fellows perform better may be that units in experimental sciences benefit more from experienced researchers capable of raising large amounts of funds, since such units need to be equipped with sophisticated machinery in order to run experiments. The fact that, conversely, the best Social Science units are relatively younger may signal that in some disciplines, such as Economics and Statistics, methodological and technical innovations appear quite frequently: because younger fellows run faster down the learning curve, units with a lower average age are better able to implement such innovations.

The age of the research institution is positively and significantly associated with the number of excellent publications in all fields and in the Social Science sample, but not in Science. The reputation-elasticity of excellent products, however, is small (nearly 5% in all fields, slightly below 10% in Science, and about 8% in Social Science). Allison and Long (1990) showed that the productivity of researchers increases after they move to more prestigious scholarly institutions, possibly because reputation enables them to raise funds more easily (Cole 1970). However, our results suggest that older institutes are only marginally able to exploit their larger stock of organizational experience or to attract talented researchers.

5 Conclusion

In this paper, we have investigated the effects of co-authorship and other forms of social interactions in science on the productivity of scientists. This issue has become crucial in any debate on policies to foster science in advanced countries, because nowadays the phenomenon of collaboration is widely diffused in the community of researchers. We approached the issue empirically by relying on data from the first assessment of the research outputs of 102 Italian universities and research organizations, both public and private. The data refer to 20 disciplines, and have several positive features, among which the most important is that research products have been assigned to five different quality categories through a process of peer evaluation, which is more reliable than the common use of metric-based indicators. We have specified a Negative Binomial model for count data and obtained estimates for a sample including all fields, as well as for subsamples of units active in science and in social science. Overall, the results confirm the importance of collaborations among scientists in enhancing the quality of the publications. This is particularly true for collaborations with researchers affiliated to other organizations and for international mobility: both have positive effects on the production of high quality papers. The overall set of regression results has strong implications for science policy, since it underlines how knowledge exchange with researchers in the global science community are vital for those who aim at achieve the highest quality of research, and have limited or even negative effects on those who do not compete for international prestige in academic research. Further research should be devoted to a deeper understanding of the motivations and channels of knowledge exchange among scientists.

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Variable	n. obs.	min	median	max	mean	sd	cv
Whole sample							
Excellent publications	1065	0	2	367	5.4441	15.615	2.8683
Good publications	938	0	4	245	9.0501	16.300	1.8011
Acceptable publications	938	0	2	79	3.5192	6.0413	1.7167
FTE researchers	1096	0	13.5	1319.3	33.750	70.638	2.0930
Own funds	1096	0	12	712	22.330	45.296	2.0284
Investments	1096	0	0	18250	1240.2	2273.3	1.8330
Avg. researchers' age	842	28	44.877	56	44.690	3.6626	.0820
Age of the unit	1093	4	80	916	242.43	288.41	1.1896
Staff per FTE researcher	1096	0	.13011	11.258	.3548	.7885	2.2226
PhD students per FTE researcher	1096	0	.7	25.5	1.1256	1.8924	1.6811
Share of external coauthors	939	0	.24	.97	.2636	.2200	.8346
Authors per FTE researcher	939	.0826	1.4737	110.16	3.2378	7.7448	2.3920
Res. in international mobility	1096	0	0	107.1	2.1109	6.7734	3.2087
Science							
Excellent publications	588	0	2	367	6.8248	20.1259	2.9489
Good publications	517	0	4	245	11.0445	20.5960	1.8648
Acceptable publications	517	0	1	79	3.8182	7.3633	1.9285
FTE researchers	605	0	13.2	1319.3	39.8418	89.6451	2.2500
Own funds	605	0	16	712	26.7506	53.8835	2.0143
Investments	605	0	0	18250	1359.50	2421.31	1.7810
Avg. researchers' age	456	28	44.051	56	43.7405	3.7101	.0848
Age of the unit	605	5	80	916	242.549	289.980	1.1956
Staff per FTE researcher	605	0	.1264	11.2575	.4217	.9927	2.3542
PhD students per FTE researcher	605	0	.7	25.5	1.1410	1.9403	1.7001
Share of external coauthors	518	0	.35	.97	.3723	.2054	.5519
Authors per FTE researcher	518	.0826	2.0876	110.16	4.4553	9.6104	2.1571
Res. in international mobility	605	0	0	107.1	2.7803	7.9423	2.8566
Social Science							
Excellent publications	343	0	2	58	4.3499	7.0835	1.6284
Good publications	295	0	5	50	7.2712	8.0678	1.1096
Acceptable publications	295	0	2	25	3.2508	3.7884	1.1654
FTE researchers	347	0	17.7	198.2	29.1764	33.8816	1.1613
Own funds	347	0	10	366	16.2565	26.2966	1.6176
Investments	347	0	0	12194	965.346	1904.11	1.9725
Avg. researchers' age	275	34.5	46.214	56	45.986	3.3681	.0732
Age of the unit	344	4	79	916	229.808	282.666	1.2300
Staff per FTE researcher	347	0	.1811	2.23966	.2920	.3572	1.2234
PhD students per FTE researcher	347	0	.9	24.3	1.2386	1.8323	1.4793
Share of external coauthors	295	0	.04	.75	.0975	.1361	1.3960
Authors per FTE researcher	295	.1408	.6081	14	.7907	.8799	1.1127
Res. in international mobility	347	0	0	96	1.5896	5.5795	3.5100

Table 1: Summary statistics: All fields, Science, and Social Science fields.

Table 2: Estimated coefficients for the Negative Binomial regression. Dependent variable: number of publications of quality q, with $q \in \{$ Excellent, Good, Acceptable $\}$. The sample includes units active in all fields.

Regressors	**Exc. Publ.**		**Good Publ.**		**Acceptable Publ.**	
	coeff.	t	coeff.	t	coeff.	t
ln researchers	.7943	7.17	.8266	13.99	1.0719	9.65
ln avg. researchers' age	.1373	0.18	-.2353	-0.62	.0145	0.03
ln age of the unit	.0487	2.23	.1557	1.35	-.0145	-0.79
ln staff	.8319	2.54	.3913	2.47	-.5954	-1.76
ln phd	-.0883	-0.94	.0066	0.11	-.0657	-0.75
share external coauthors	.5754	1.94	-.6635	-4.21	-1.5273	-6.33
ln authors per researcher	.1689	2.09	.3347	7.61	.5691	6.67
ln international mobility (pred.)	1.2291	4.39	.2218	1.39	-1.2503	-4.60
constant	-2.0483	-0.74	-.3307	-0.24	-1.8653	-0.85
		std.err.		std.err.		std.err.
α	.0852	.0207	.0024	.0220	.0474	.0276
n. observations	645		644		644	
Log-likelihood	-1275.19		-1387.08		-1145.01	
pseudo-R^2	.28		.33		.25	

Likelihood-ratio test of $\alpha = 0$:
$\overline{\chi}^2(01) = 85.83$, $Prob \geq \overline{\chi}^2 = 0.000$ (excellent publ.)
$\overline{\chi}^2(01) = 0.42$, $Prob \geq \overline{\chi}^2 = 0.259$ (good publ.)
$\overline{\chi}^2(01) = 12.70$, $Prob \geq \overline{\chi}^2 = 0.000$ (acceptable publ.)

Table 3: Estimated coefficients for the Negative Binomial regression. Dependent variable: number of publications of quality q, with $q \in \{$ Excellent, Good, Acceptable $\}$. The sample includes units active in the Science fields.

Regressors	**Exc. Publ.**		**Good Publ.**		**Acceptable Publ.**	
	coeff.	t	coeff.	t	coeff.	t
ln researchers	.4704	2.42	.8266	13.99	1.1323	6.14
ln avg. researchers' age	2.4364	2.09	-.5458	-0.99	-.8035	-0.80
ln age of the unit	.0978	2.09	.0143	0.65	-.0601	-1.85
ln staff	1.6443	3.32	.0933	0.31	-.9575	-1.79
ln phd	-.0861	-0.65	-.0689	-0.84	-.0533	0.40
share external coauthors	.6737	2.27	-.5482	3.30	-1.5896	-4.77
ln authors per researcher	.0701	0.69	.2691	3.41	.5748	3.78
ln international mobility (pred.)	1.8068	4.24	-.0826	-0.31	-1.6425	-2.76
constant	-10.1297	-2.45	.7080	0.37	1.2121	0.34
		std.err.		std.err.		std.err.
α	.0790	0.0279	.0035	.1060	.0611	.3307
n. observations	339		338		338	
Log-likelihood	-714.30		-741.41		-594.41	
pseudo-R^2	0.28		0.35		0.26	

Likelihood-ratio test of $\alpha = 0$:
$\overline{\chi}^2(01) = 55.28$, $Prob \geq \overline{\chi}^2 = 0.000$ (excellent publ.)
$\overline{\chi}^2(01) = 0.53$, $Prob \geq \overline{\chi}^2 = 0.234$ (good publ.)
$\overline{\chi}^2(01) = 10.85$, $Prob \geq \overline{\chi}^2 = 0.000$ (acceptable publ.)

Table 4: Estimated coefficients for the Negative Binomial regression. Dependent variable: number of publications of quality q, with $q \in \{$ Excellent, Good, Acceptable $\}$. The sample includes units active in the Social Science fields.

Regressors	**Exc. Publ.**			**Acceptable Publ.**	
	coeff.	t		coeff.	t
ln researchers	1.1443	6.54		1.0170	9.28
ln avg. researchers' age	-2.7097	-3.06		.9395	0.80
ln age of the unit	.0771	1.65		.0217	-0.44
ln staff	-.0709	-0.15		-.1634	-0.47
ln phd	-.1759	-1.31		-.1207	-0.96
share external coauthors	1.7457	2.40		-1.6233	-3.02
ln authors per researcher	.0853	0.44		.3883	2.60
ln international mobility (pred.)	.7785	2.91		-.6610	-1.57
constant	7.2207	2.22		-4.6667	-1.03
		std.err.		std.err.	
α	.0526	.3314		.0484	.5211
n. observations	214		214		
Log-likelihood	-404.84		-397.54		
pseudo-R^2	0.31		0.22		

Likelihood-ratio test of $\alpha = 0$:

$\overline{\chi}^2(01) = 12.46$, $Prob \geq \overline{\chi}^2 = 0.000$ (excellent publ.)

$\overline{\chi}^2(01) = 3.75$, $Prob \geq \overline{\chi}^2 = 0.026$ (acceptable publ.)

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Appendix

Research institutions in the 2001-2003 Italian research assessment.

Universities

Universitá degli Studi di BARI
Politecnico di BARI
LUM Jean Monnet
Universitá degli Studi della BASILICATA
Universitá degli Studi di BERGAMO
Universitá degli Studi di BOLOGNA
Libera Universitá di BOLZANO
Universitá degli Studi di BRESCIA
Universitá degli Studi di CAGLIARI
Universitá della CALABRIA
Universitá degli Studi di CAMERINO
Universitá degli Studi di CASSINO
Universitá Carlo Cattaneo - LIUC
Universitá degli Studi di CATANIA
Universitá degli Studi Magna Graecia di CATANZARO
Universitá degli Studi G. d'Annunzio CHIETI-PESCARA
Universitá degli Studi di FERRARA
Universitá degli Studi di FIRENZE
Universitá degli Studi di FOGGIA
Universitá degli Studi di GENOVA
Universitá degli Studi INSUBRIA Varese-Como
Universitá degli Studi de L'AQUILA
Universitá degli Studi del SALENTO
Universitá degli Studi di MACERATA
Universitá degli Studi di MESSINA
Universitá degli Studi di MILANO
Universitá degli Studi di MILANO-BICOCCA
Politecnico di MILANO
Universitá Commerciale Luigi Bocconi MILANO
Universitá Cattolica del Sacro Cuore
Libera Universitá di lingue e comunicazione IULM-MI
Libera Universitá Vita Salute S.Raffaele MILANO
Universitá degli Studi di MODENA e REGGIO EMILIA
Universitá degli Studi del MOLISE
Universitá degli Studi di NAPOLI Federico II

Seconda Universitá degli Studi di NAPOLI
Universitá degli Studi di NAPOLI Parthenope
Universitá degli Studi di NAPOLI L'Orientale
Universitá degli Studi Suor Orsola Benincasa - NAPOLI
Universitá degli Studi di PADOVA
Universitá degli Studi di PALERMO
Universitá degli Studi di PARMA
Universitá degli Studi di PAVIA
Universitá degli Studi di PERUGIA
Universitá per Stranieri di PERUGIA
Universitá degli Studi del PIEMONTE ORIENTALE Amedeo Avogadro-Vercelli
Universitá degli Studi di PISA
Scuola Normale Superiore di PISA
Scuola Sup. di Studi Univ. e Perfezionamento S.Anna di PISA
Universitá Politecnica delle MARCHE
Universitá degli Studi Mediterranea di REGGIO CALABRIA
Universitá degli Studi di ROMA La Sapienza
Universitá degli Studi di ROMA Tor Vergata
Universitá degli Studi ROMA TRE
Universitá Campus Bio-Medico ROMA
Istituto Universitario di Scienze Motorie di ROMA
Libera Univ. Inter.le Studi Sociali Guido Carli LUISS-ROMA
Libera Universitá degli Studi S. Pio V ROMA
Libera Univ. degli Studi Maria SS.Assunta - LUMSA - Roma
Universitá degli Studi di SALERNO
Universitá degli Studi del SANNIO di BENEVENTO
Universitá degli Studi di SASSARI
Universitá degli Studi di SIENA
Universitá per Stranieri di SIENA
Universitá degli Studi di TERAMO
Universitá degli Studi di TORINO
Politecnico di TORINO
Universitá degli Studi di TRENTO
Universitá degli Studi di TRIESTE
Scuola Internazionale Superiore di Studi Avanzati di TRIESTE
Universitá degli Studi della TUSCIA
Universitá degli Studi di UDINE
Universitá degli Studi di URBINO Carlo BO
Universitá della VALLE D'AOSTA

Universitá Ca' Foscari di VENEZIA
Universitá IUAV di VENEZIA
Universitá degli Studi di VERONA

Research centers

Biotecnologie Avanzate
Biotecnologie e Genetica Molecolare nel Mezzogiorno
Centro di Ricerca in Matematica Pura e Applicata
Consiglio Nazionale delle Ricerche
Consorzio Interuniversitario Nazionale per la Chimica e l'Ambiente
Consorzio Interuniversitario Nazionale per la Scienza e Tecnologia dei Materiali
Consorzio Univ. di Economia industriale e Manageriale
Elettra Sincrotrone Trieste
Ente per le Nuove tecnologie, per l'Energia e l'Ambiente
Fondazione per le Scienze Religiose Giovanni XXIII
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Istituto Nazionale di Oceanografia e di Geofisica Sperimentale
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