

# Analysis of Slovenian research community through bibliographic networks

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Received: 7 June 2016 / Published online: 10 December 2016  
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**Abstract** Science is a societal process, designed on widely accepted general rules which facilitate its development. Productive researchers are viewed from the perspective of a social network of their interpersonal relations. In this paper we address performance of Slovenian research community using bibliographic networks between the years 1970 and 2015 from various aspects which determine prolific science. We focus on basic determinants of research performance including productivity, collaboration, internationality, and interdisciplinarity. For each of the determinants, we select a set of statistics and network measures to investigate the state of each in every year of the analyzed period. The analysis is based on high quality data from manually curated information systems. We interpret the results by relating them to important historical events impacting Slovenia and to domestic expenditure for research and development. Our results clearly demonstrate causal relations between the performance of research community and changes in wider society. Political and financial stability together with concise measuring of scientific productivity established soon after Slovenia won independence from Yugoslavia in 1991 had positive influence on all determinants. They were further leveraged by foundation of Slovenian research agency and joining EU and NATO. Publish and perish phenomenon, negative impacts of financial crisis in 2008–2014 and reshaping the domestic expenditure for research and development after 2008 have also clear response in scientific community. In the paper, we also study the researcher’s career productivity cycles and present the analysis of the career productivity for all registered researchers in Slovenia.

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**Keywords** Research performance · Network analysis · Productivity · Scientific collaboration · Internationality · Interdisciplinarity

## Introduction

The creation of science is a societal process. To resolve highly reticular and complex problems that are at the center of modern socio-technical systems, researchers need to develop new ways of doing science (Shneiderman 2008). In this regard creative and productive researchers are viewed from the perspective of a network of their interpersonal relations. This has fundamentally changed the structure and organizational culture in many scientific domains. The collaboration of researchers has become the condition *sine qua non* for prolific science. Bozeman and Corley (2004) argued that collaboration is among major factors in promoting and transmitting scientific and technical human capital. Today, research teams increasingly outshine solo authors in the production of knowledge (Wuchty et al. 2007). Team work facilitates the process of knowledge creation and enhances the possibility of exploiting research findings. Collaboration among researchers contributes to cross-fertilization of scientific ideas (Katz and Martin 1997) and significantly correlates to the quality of research papers (He et al. 2009). Studies have shown that the probability of collaboration increases with closer physical proximity (Katz 1994). Number of authors per publication has risen regularly since 1980 (Waltman et al. 2011). Collaborative behavior includes divergent mental perspectives and stimulates new intuitions into complex research problems. Nowadays, the collaboration between researchers is mainly measured in terms of coauthorships of scientific papers. Globalization in science should therefore manifest in tightly connected research platforms in which all actors are likely to serve as collaborators.

Interdisciplinary research aims to integrate more disparate scientific disciplines to create new scientific fields. The main purpose of interdisciplinarity is to solve scientific problems that are apart from scope of a single research discipline. For instance, under the umbrella of psycho-informatics, statisticians, computer scientists, and psychologists combine their techniques and research tools to derive new insights about human mind (Yarkoni 2012). Other examples include bioinformatics and a bundle of ‘omics’ sciences (e.g., metabolomics, pharmacogenomics, populomics, etc.). Recent empirical evidence stress the significance of interdisciplinarity in research process for revolutionary scientific discoveries (Uzzi et al. 2013). During the past several hundred years the science was, without exception, monodisciplinary. However, in the last two decades it seems that the historical moment is mature enough for the integration of accumulated knowledge for understanding the complex technological world that has emerged (Ball 2012). Indeed, as empirical results demonstrated, science is becoming more interdisciplinary, but in smaller steps. Research knowledge transfer is mainly limited to neighboring scientific fields and only a small proportion of connections is due to distant cognitive areas (Porter and Rafols 2009).

Science has also become enormously globalized. New scientific results could be communicated worldwide immediately with one mouse click. Intellectual exchange in research communities is an essential characteristics of scientific work. Internationality may be quantified through collaborative papers, informal contacts, fellows among countries, and participation in conferences. It results mainly from the raising costs of research resources and government policies to favor globalization. This is additionally stimulated with the increasing importance of English language as *lingua franca* in most scientific

fields. The past decades witnessed a strong increase of international collaboration. Internationality is influenced by at least two main components: (1) country size and (2) ‘remoteness’ (Glänzel and Schubert 2005). However, the understanding of the dynamics of the science at the global level is still at its infancy. It is silently assumed that internationality positively correlates with quality of research and that it should be encouraged (Katz and Martin 1997).

## Contribution

The purpose of this paper is to provide a comprehensive analysis of Slovenian research community in the time span 1970–2015 with focus to productivity, collaboration, internationality and interdisciplinarity of Slovenian researchers. Similar analyses investigating collaboration (Perc 2010a; Kronegger et al. 2011; Ferligoj et al. 2015; Karlovčec et al. 2016), interdisciplinarity (Karlovčec and Mladenić 2015; Lužar et al. 2014), and citation distribution (Perc 2010b) in Slovenia have already been performed. We refer an interested reader to Ferligoj et al. (2015) and the references therein for more details about the research of scientific performance in Slovenia.

We used all available data about scientific production and about registered researchers from two high quality information systems, Co-operative Online Bibliographic System and Service (COBISS)<sup>1</sup> and Slovenian Current Research Information System (SiCRIS),<sup>2</sup> which are maintained by the public Institute of information science (IZUM)<sup>3</sup> and Slovenian research agency (ARRS),<sup>4</sup> and analyzed it using network analysis approach. The main contributions of this paper are twofold:

- We used various network measures to analyze four aspects of research community performance: productivity, collaboration, internationality, and interdisciplinarity. We evaluated them for the case of Slovenian researchers in the time span 1970–2015, and studied how they correlate between each other. We related the results with historical milestones and demonstrated how important historical events or periods reflect in scientific performance.
- We computed and analyzed the career productivity cycles of Slovenian researchers by determining for every researcher how many publications she published in total in her *i*-th publication year (see the definition on page 10). Results show that the number of active researchers is rapidly decreasing with time. However, those who remain active for more than 20 years stay active until the end of their careers.

## Time frame and milestones

In this paper we study performance of Slovenian research community between the years 1970 and 2015 (inclusive). In this period Slovenia faced a number of structural changes that considerably affected the research society, including changes of the political system, monetary system, several economic crises, changes in the structure of the research

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<sup>1</sup> [http://www.cobiss.si/cobiss\\_eng.html](http://www.cobiss.si/cobiss_eng.html).

<sup>2</sup> <http://www.sicris.si/public/jqm/cris.aspx?lang=eng&opdescr=home&opt=1>.

<sup>3</sup> <http://www.izum.si/default-EN.htm>.

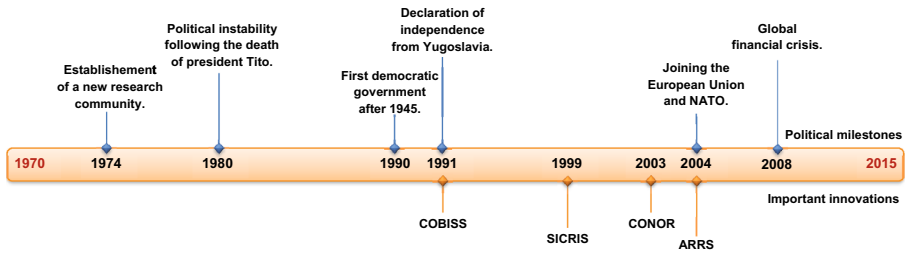
<sup>4</sup> <http://www.arrs.gov.si/en/index.asp>.

community, etc. We first list some of the most important political milestones from this period (the list is mostly based on Novak and Demšar (2012)):

- 1974 Adoption of new constitutional law of Socialist Federal Republic of Yugoslavia (to which Slovenia belonged) was followed by new Research Communities Act. This led to new self-managing organization of Slovenian researchers. The research policy in the following years was mainly influenced by the interests of the researchers and the users of the results were almost neglected (Novak and Demšar 2012).
- 1980 The death of the longstanding Yugoslav president Tito was followed by big political instability. This was accompanied by deep economic and debt crisis in the country and abroad, resulting in decreasing funding of science. The number of new doctors decreased, many R&D departments in business sector were reduced or completely closed down. However, in late 1980s the trends in Slovenia went up again and in 1987 the state funding of research reached 0.7% of GDP. All these ups and downs resulted in a big instability in Slovenian research community and were demonstrated also in fluctuations in the scientific performance of the community.
- 1990 In this year Slovenia elected the first democratic government after 1945. A year after Slovenia declared and defended its independence from Yugoslavia after a short-period military aggression. A new economic crisis started, loss of traditional markets and consequent turning focus to new economic areas.
- 2004 After more than five year long period of efforts invested in many reforms aiming to fulfill the entering criteria, Slovenia joined NATO and European Union.
- 2008 Slovenia faced big financial and depth crisis with negative impact on budgetary financing of R&D. However, private investment in R&D increased and balanced the public shortfall. The crisis officially ended in 2014.

Apart from political stimuli, several innovations within Slovenian research community turned out to be very influential. (The details are obtained from IZUM and ARRS web pages.)

- 1991 The COBISS system developed by IZUM was introduced. In the following years this enabled collecting concise bibliographic records for all Slovenian authors and afterwards also complete bibliographies for all Slovenian researchers.
- 1999 The new information system SiCRIS, aiming to contain up-to-date information about the Slovenian research community, was launched. Nowadays this is the main, high quality public source of information related to Slovenian researchers, research organizations, research projects and programs, etc. It is directly connected to COBISS in parts where bibliographic data of researchers is required. Researchers who have taken part in Slovenian Research Agency projects since 1998, or whose active status has been either registered or confirmed by the research organizations, are included in SiCRIS. Our small and non-systematic research shows that the most productive researchers retired before 1998 are still included in the SiCRIS while some mediocre are missing and also some of their bibliographic items are missing in the COBISS. Despite this missing data we are confident that the available data is representative for the period 1970–1998.
- 2003 The CONOR database was introduced by IZUM. It enables clear identification of all bibliographic records related to the same author under all variants of her name. In particular, we can identify all coauthors of registered authors, thus identifying



**Fig. 1** Timeline of important historical events. Above the line, the political milestones are presented, research innovations are listed below the timeline

the degree of international collaboration, since coauthors not registered in SiCRIS are with high probability foreign.

2004 The ARRS agency was formed and put in charge of creating operational research policy and budgetary funding of the Slovenian research community. Soon after a systematic and stable support of research via research programs started, additional support was provided through research projects, international cooperation, junior researcher fellowship programs and infrastructure development. These support mechanisms are still active at present.

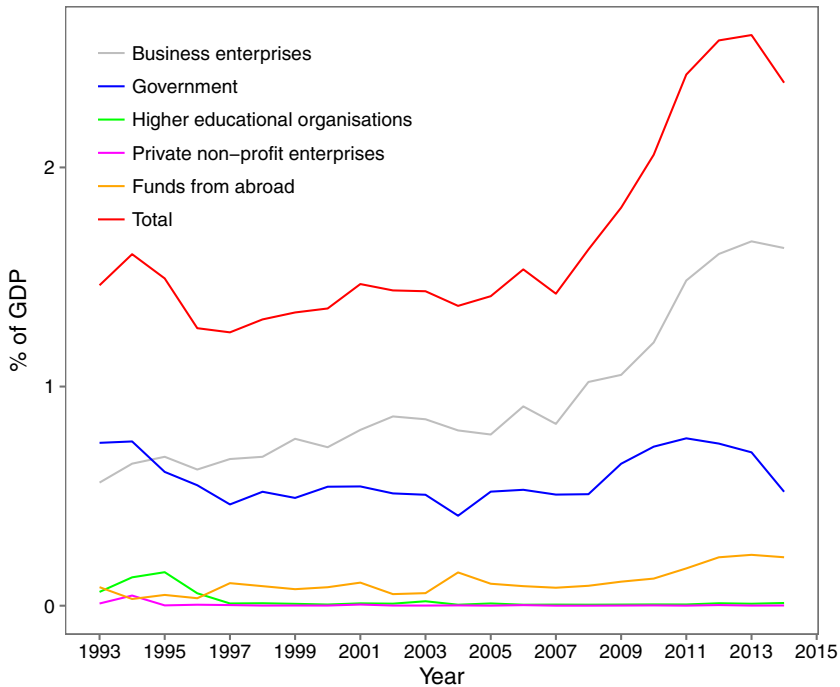
The political milestones and research innovations listed above are presented in Fig. 1. We also collected the data about budgetary and non-budgetary expenditure for R&D in Fig. 2.

### Data and methodology description

For this research, we use the data about researchers registered in SiCRIS (referred to as *registered researchers*) and the publications they coauthored obtained from COBISS. Every registered researcher in Slovenia is assigned a unique identification code in SiCRIS database through which it is related to the publications in COBISS database she coauthored. In particular, in this analysis we consider:

- (a) The set  $A$  comprised of all registered researchers that published at least one scientific publication<sup>5</sup> in the period from 1970 to 2015 (inclusive). When we consider only the researchers from  $A$  who published at least one publication in a year  $y$  we denote this set by  $A_y$  and call it the *set of productive researchers in a year  $y$* ; consequently, every researcher belonging to some set  $A_y$  is *productive* in the respective year. Clearly we have  $A = \cup_{y=1970}^{2015} A_y$ .
- (b) The set  $P$  comprised of all scientific publications published between 1970 and 2015, and being coauthored by at least one registered researcher. The subset of publications published in a year  $y$  is denoted by  $P_y$ . We have  $P = \cup_{y=1970}^{2015} P_y$  and the union is exclusive, i.e.,  $P_y \cap P_z = \emptyset$  for  $y \neq z$ . By  $P_y(r)$  we denote the set of all publications from  $P_y$  coauthored by the researcher  $r$  in a year  $y$ , hence  $P_y = \cup_{r \in A_y} P_y(r)$ .

<sup>5</sup> We say that a publication is *scientific* if it is classified as an *original scientific article*, a *review article*, a *short scientific article*, a *published scientific conference contribution*, a *published scientific conference contribution abstract*, an *independent scientific component or a chapter in a monograph*, or a *scientific monograph*.



**Fig. 2** Budgetary financing of R&D in Slovenia for 1993–2014. (Source: Statistical Office of the Republic of Slovenia, 2016). (Color figure online)

We point out again that COBISS database started only in 1991, so the bibliographic records after 1991 show complete picture of productivity of Slovenian researchers while the data about publications published before 1991 were entered later (after 1991) and probably lack some entries.

Using the collected data, we construct a 2-mode bibliographic network  $\mathcal{N}^{p-r}$  ('publication-researcher' networks) with partitions of vertices equal to  $P$  and  $A$ . A publication  $p \in P$  and a researcher  $r \in A$  are connected in  $\mathcal{N}^{p-r}$  if  $r$  coauthored  $p$ . The 2-mode network defined by  $P_y$  and  $A_y$  is denoted by  $\mathcal{N}_y^{p-r}$ .

We also constructed the 1-mode bibliographic network (also called *coauthorship* or *collaboration* network)  $\mathcal{N}^{r-r}$  ('researcher-researcher' network) from  $\mathcal{N}^{p-r}$ . This is a network connecting researchers that coauthored a joint publication. We weight the edges by the number of joint publications between the two researchers being connected by an edge. We denote by  $\mathcal{N}_y^{r-r}$  the 1-mode network representing  $A_y$  and  $P_y$ . The weights of edges in  $\mathcal{N}_y^{r-r}$  correspond to the number of joint publications in the year  $y$ . As customary, by  $N(x)$ , we denote the neighborhood of a vertex  $x$  in given network. This in particular means that for every researcher  $r$  from  $A_y$ ,  $N(r)$  is comprised of all publications from  $P_y$  that  $r$  has coauthored, when we consider  $\mathcal{N}_y^{p-r}$  and is the set of coauthors of  $r$  of publications from  $P_y$ , if we consider  $\mathcal{N}_y^{r-r}$ .

For the purpose of this analysis, we use also some additional data about researchers and publications. (Almost) every registered researcher  $r$  is classified into one or more out of seven main research fields due to SiCRIS database. The first six research fields are respectively *Natural sciences and mathematics*, *Engineering sciences and technologies*,

*Medical sciences, Biotechnical sciences, Social sciences, and Humanities.* There is however a minor number of researchers that are, for some reason, not classified into any science field—in our case about 80 among almost 23,000 different researchers in the entire interval. We ignore these researchers in the analysis of interdisciplinarity. There is also another inconsistency with the data, also commented recently by Rodela (2016). In particular, there is no publicly available tracking of updates about researchers’ field of research changes. However, according to SiCRIS support service, the number of changes of these property is equal to 915 in the period from the year 2001 till present in which the changes are recorded. The data is hence representative, and we are confident that our analysis reveals the trends in interdisciplinarity accurately.

We use the classification to define a six-component *classification vector*  $\text{class}(r)$  for every researcher  $r$  in the following way: let  $f_r$  be the number of research fields  $r$  is classified in. Then the  $i$ -th component of  $\text{class}(r)$  is equal to  $\frac{1}{f_r}$  if  $r$  is classified into the  $i$ -th field and zero otherwise. The seventh research field is denoted *Interdisciplinary studies* and it is rarely used compared to other fields. It is also not determined in which fields a researcher, classified into this field, is active. Therefore we ignore the seventh field, and whenever  $r$  is classified exclusively as interdisciplinary, we do not consider her classification contribution in computations of interdisciplinarity. Note that the sum of all six components of every classification vector equals 1.

For every publication  $p$  from  $P$ , apart from the list of registered researchers and the year in which  $p$  was published, we know the number of all coauthors  $\text{aut}(p)$  of  $p$ , which includes registered and non-registered researchers. We have even a complete list of publication authors  $\text{Aut}(p)$  for every publication  $p$  published in the years after the CONOR database was introduced in 2003 (note that for such publications  $p$ , the set  $N(p)$  is a subset of  $\text{Aut}(p)$ ).

Networks can be characterized by various topological measures; we recall four of them, namely *giant component size, characteristic path length, diameter and clustering coefficient*. We computed these measures for 1-mode networks  $\mathcal{N}_y^{r-r}$ . Analysis of the results is presented in “[Collaboration](#)” section.

As the number of links between vertices increases (e.g., in time), there comes a point (i.e., percolation transition) at which the giant component of a network forms. A giant component is a large fraction (usually around 80–90% of all vertices in a network) of connected vertices. The characteristic path length of network is the average shortest path in its giant component. It is an emergent network property, which indicates how well the vertices are integrated. The length of a path is indicated by the number of the edges it contains. The diameter of the network is defined as the longest shortest path between all pairs of vertices in the giant component.

The clustering coefficient is a measure typically used in complex network analysis. It measures how likely is that two vertices sharing a common vertex are connected by an edge. We decided to measure the *average clustering coefficient* of networks  $\mathcal{N}_y^{r-r}$ , since high average clustering coefficient is a typical property of real-world networks. It is defined as average of local clustering coefficients  $C_y(r)$  (Watts and Strogatz 1998):

$$C_y = \frac{1}{|A_y|} \sum_{r \in A_y} C_y(r), C_y(r) = \frac{2m_r}{|N(r)|(|N(r)| - 1)},$$

where  $m_r$  is the number of edges between the neighbors of  $r$ . If  $N(r) \leq 1$  for some  $r \in A_y$ , we exclude  $r$  from computing  $C_y$ . High average clustering coefficient means the presence of highly connected groups of researchers in the network.

## Analysis

Over the past century science has shown a marked change from primarily single-researcher, single-discipline work to collaborative, interdisciplinary activity that exceeds national borders. In this section we analyze Slovenian scientific community from four aspects of research performance: *productivity*, *collaboration*, *internationality*, and *interdisciplinarity*. Each particular view is assessed with the most appropriate indicators that we have found in the literature, or we have created them based on the characteristics of the data we used.

### Productivity

Lotka (1926) formulated famous law of productivity in science, which stated that a relatively small proportion of researchers contribute to the majority of publications. Since Lotka's initial work, many studies have confirmed relationship between scientific productivity and collaboration. Melin (2000) emphasized that collaborations are characterized by strong personal pragmatism and high degree of self-organization. Zuckerman (1967) found that Nobel prize winners published more and are at the same time more prone to collaborate. Pravdič and Oluić-Vuković (1986) demonstrate interesting pattern that collaboration with high-productivity researchers increase personal productivity, while collaboration with low-productivity scientists generally decreases it. Lee and Bozeman (2005) found that amount of peer-reviewed journal papers is strongly associated with the number of collaborators. However, when publishing productivity is measured by dividing credit by the number of coauthors, productivity and collaboration are not significantly related anymore. Researchers at the research institutes are more likely to collaborate than their colleagues at the universities (Boardman and Corley 2008).

The productivity of research community of a country is measured in different ways. For example, Kim et al. (2016) used the cumulative number of publications (i.e., the total number of publications in and before a given year), while Mena-Chalco et al. (2014) used the cumulative number of publications considering last three years. We conducted a bit more comprehensive analysis of the productivity. For each year  $y$  from the time span 1970–2015 we measured:

- The number of all publications, i.e.,  $|P_y|$ .
- The number of productive researchers, i.e.,  $|A_y|$ .
- The number of all distinct authors of publications in  $P_y$  from the year 2003 on, i.e., productive researchers  $A_y$  and non-registered coauthors, which are mostly foreign coauthors. The analysis is performed only from 2003 because only since then  $\text{Aut}(p)$  can be identified for each  $p \in P_y$ , due to CONOR database deployment.

For better understanding we consider two additional measures of relative productivity (see Fig. 5):

- the average number of publications per author in a given year  $y$  is defined as the average degree of  $A_y$  partition of  $\mathcal{N}_y^{p-r}$ , i.e.,

$$\frac{\sum_{r \in A_y} |P_y(r)|}{|A_y|}.$$

- the average fractional number of publications per productive researcher in a year  $y$ :



$$\frac{\sum_{r \in A_y} \sum_{p \in P_y(r)} \frac{1}{\text{aut}(p)}}{|A_y|}$$

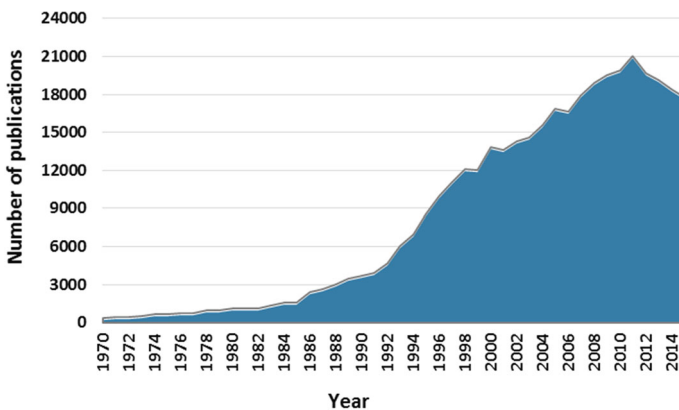
This indicator was introduced by Lindsey (1980) and it is also known as fractional counting of publications.

The indicators described above are visualized in Figs. 3, 4 and 5.

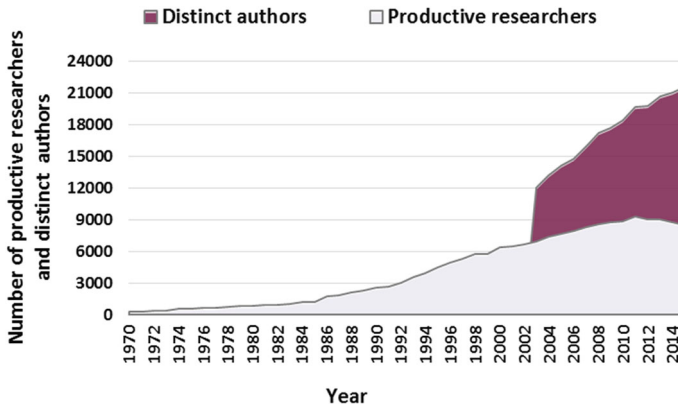
In the scope of studying productivity, we also analyzed the *career productivity cycle* of registered researchers in the time span 1970–2015. This concept was already introduced by Lee and Bozeman (2005). For every registered researcher  $r$ , we detected  $\text{start}(r)$ , the year in which she first coauthored a publication from  $P$ , and analogously,  $\text{end}(r)$ , the year she published her last publication from  $P$ . The  $r$ 's *publication career* therefore spans over the years  $i = 1, 2, \dots, \text{end}(r) - \text{start}(r) + 1$ . For each publication career year (PCY) we compute the number of active and productive researchers.

A researcher  $r$  is (still) *active* in PCY  $i$  if she has published at least one publication in the corresponding year or later (i.e.,  $i \leq \text{end}(r) - \text{start}(r) + 1$ ). Likewise, we say that a researcher  $r$  is *productive* in PCY  $i$  if she has published at least one publication in the corresponding year. The dynamics of the number of active and productive researchers is presented in Fig. 6, while Fig. 7 depicts the *career productivity* of the active researchers through career span, i.e., for each triennium of PCYs we draw a box plot showing the minimum, 1st, 2nd, 3rd quartile and maximum number of publications of all researchers that are active in the considered period (outliers are excluded from the box plots. i.e. if maximum is greater than the 3rd quartile plus 1.5 times interquartile range (IQR), we plot the latter). Additional curve shows the average career productivity, i.e., the total number of all publications published in each PCY, divided by the number of all active researchers in the corresponding PCY.

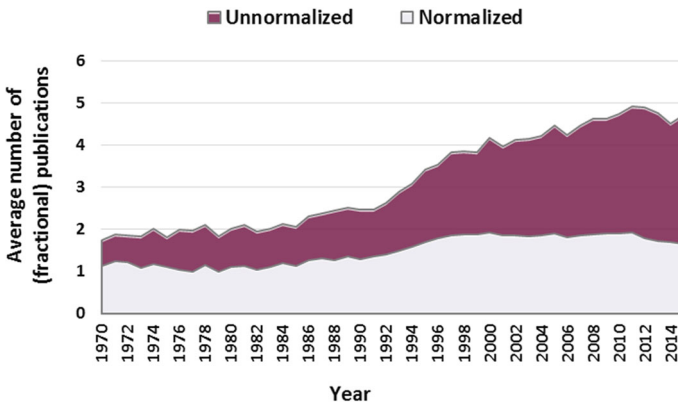
Figure 3 demonstrates that the scientific productivity has started increasing fast after the year 1992. This is likely to be a result of a more competitive atmosphere in Slovenia due to political changes in the years 1990–1991 and an introduction of COBISS database, which became a public evidence of publishing efforts. The productivity reached the peak in 2011 when all registered researchers have published in total slightly more than 21,000 publications.



**Fig. 3** The number of scientific publications has been growing from the beginning of the analyzed period and started increasing fast after the year 1992. An almost linear growth between 1992 and 2012 is evident



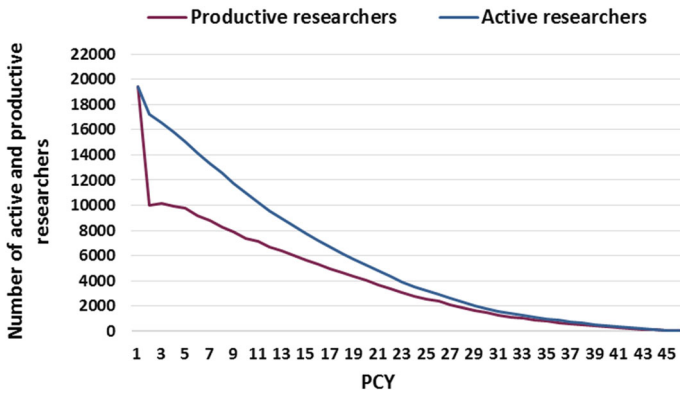
**Fig. 4** Similarly as the number of publications, the number of productive researchers has been growing until the peak in 2011. The number of all distinct authors of recorded scientific publications is growing even faster, but the data is complete only since the year 2003. (Color figure online)



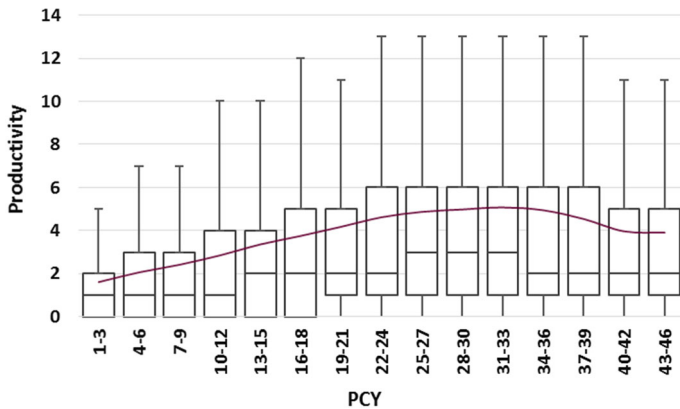
**Fig. 5** The average (fractional) number of publications per productive researcher per year is perhaps the most descriptive when considering productivity. It is evident that the fractional number of publications is more or less stable over the years with a slight increment in the middle of the 90s. On the other hand, the number of publications a researcher coauthors within a year is growing. (Color figure online)

The number of productive researchers (see Fig. 4) has been increasing until 2011, when it started decreasing. On the other hand, the number of all distinct authors from the year 2003 is increasing constantly. Figure 5 depicts that the average number of publications per author has increased a lot in the period 1970–2010, especially in period 1992–2010, while the average fractional number of publications is not varying a lot and demonstrates slight decrease in the years 2011–2015.

In our opinion, the decline in productivity in the years 2012–2015 is mainly due to the decrement of productive researchers. The main reason behind this decline is likely to be decreasing of the total state expenditure for R&D after 2010, while the gross expenditure for R&D was still increasing due to higher investments in private sector (see Fig. 2). Therefore many researchers, especially younger researchers, moved from state research or higher education institutions to private R&D departments and their focus changed from



**Fig. 6** The number of active and productive researchers through career spans are presented in the chart. For the PCY 1 and PCY 46 are the numbers of active and productive researchers the same by the definition. In the years following PCY1 both numbers are clearly decreasing, due to non-balanced career spans the researchers in consideration have. (Color figure online)



**Fig. 7** Productivity of active researchers through career spans. One can observe that the average career productivity increases until PCY 35 which coincides with usual retirement of academic staff, but the numbers remain considerably high also after

scientific writing towards market oriented R&D. The Statistical Office of the Republic of Slovenia (SURs) reports<sup>6</sup> that the number of researchers with PhD in private sector is in 2012 for 84% higher compared to the number in 2009. An important side effect of decreased state investments in R&D is also a decrement in the number of researchers in junior researcher fellowship program, which decreased from about 1400 in 2011 to 1050 in 2014 and will result in further decrease of productivity in the following years.<sup>7</sup> An additional reason could be also the brain drain effect after the year 2008. However, SURs reports that among Slovenian citizens aged 25–39 that lived abroad on January 1st 2015

<sup>6</sup> [http://pxweb.stat.si/pxweb/database/Ekonomsko/23\\_raziskovanje\\_razvoj/04\\_Kariera\\_dokt/04\\_Kariera\\_dokt.asp](http://pxweb.stat.si/pxweb/database/Ekonomsko/23_raziskovanje_razvoj/04_Kariera_dokt/04_Kariera_dokt.asp).

<sup>7</sup> <https://www.arrs.gov.si/sl/mr/obseg.asp?menu=3SCC>.

only about 300 have PhD or MSc<sup>8</sup> degree which means that brain drain effect is rather small.

We believe that *publish or perish* phenomenon can be also observed in Figs. 3, 4 and 5. The total number and the average number of publications per productive researcher have increased a lot in the years 1990–2010, but the average fractional number of publications per year is much more stable. This means that the focus of researchers has shifted to publish more (with more coauthors).

When we observe career productivity of registered researchers (Figs. 6, 7) we see that for the PCY 1 and PCY 46 are the numbers of active and productive researchers the same by the definition. In the years following PCY1 both numbers are decreasing. The highest decrement is in PCY 2 when the number of productive researchers falls from 19,187 to 9948, while the number of active researchers falls to 17,101. The main reason for this effect lies in the fact that the first few publications are typically around the PhD dissertation defense. After the PhD defence many researchers move to other business environments where publishing is not very important. They usually write a few more publications with results from the PhD dissertation in the following years and then they stop publishing.

The researchers staying in academic environment try to enhance their scientific productivity in order to obtain reputation, to be promoted to professors, or to obtain research grants. We can observe that the average career productivity increases until PCY 35 which coincides with usual retirement of academic staff. This is in line with findings from a study by Lee and Bozeman (2005). On the other hand, it seems that some academics never retire, e.g., at the time of this writing there are 50 researchers in PCY 46, who started publishing in 1970, with total of 259 publications, yielding the average career productivity for the PCY 46 equal to 5.08. Box plots from Fig. 7 also reveal that the career productivity is highly positively skewed and in each triennium from PCYs 1–18 there is a quarter of the active researchers with no publication. Likewise in trienniums from PCYs 22–39, one quarter of active researchers have at least 6 publications.

## Collaboration

Collaboration networks were empirically studied for many scientific fields (e.g., mathematics, physics, computer science, sociology, etc.) and narrower sub-fields (e.g., genetic programming, computational geometry, etc.). The most influential papers dealing with the analysis of large-scale co-authorship networks are those authored by Newman<sup>9</sup> and the properties he observed and explained (e.g., existence of giant components, small-world and scale-free properties, assortative mixing, community structures, etc.) were later confirmed in many empirical studies of collaboration networks.

Perc (2010a) was the first who studied the growth and structure of Slovenia's scientific collaboration network (from 1960 till 2010). He showed that series of networks forms small worlds and that the average path between any pair of scientists scales logarithmically with the size of the network when the giant component becomes large enough. He also found that growth of the network is controlled by near-linear preferential attachment. Besides Slovenia, similar national research collaboration studies were also performed for Korea (Kim et al. 2016), Brazil (Mena-Chalco et al. 2014), and Turkey (Çavuşoğlu and Türker 2013).

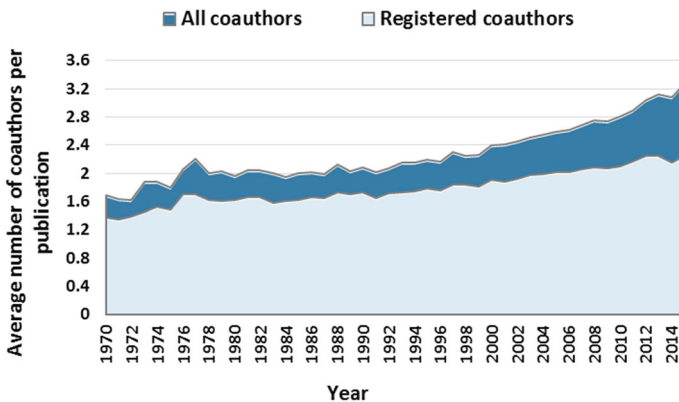
<sup>8</sup> <http://www.stat.si/StatWeb/en/show-news?id=5656&idp=17&headerbar=13>.

<sup>9</sup> <http://www-personal.umich.edu/~mejn>.

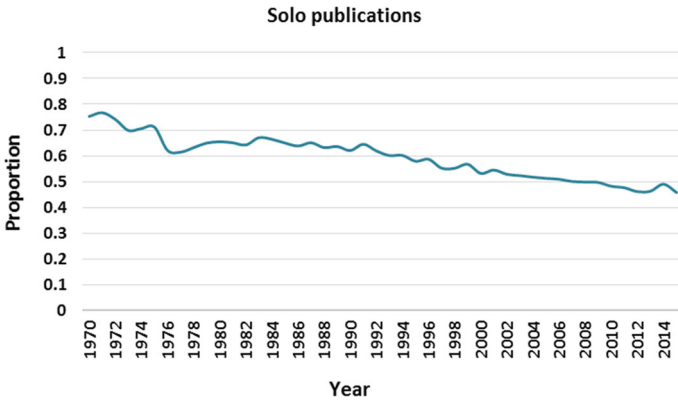
Yoshikane and Kageura (2004) found that differences between scientific domains in characteristics of coauthorship networks are mainly due to differences in research styles. Similarly, Kronegger et al. (2011) demonstrated that collaboration networks across disciplines are affected by the organization of local institutions and publishing cultures. Abbasi et al. (2012) demonstrated that scientific performance is correlated with researchers’s ego-network structure and her position in a collaboration network. Researcher who are connected to more coauthors and the one who lies more on the shortest path demonstrate greater scientific performance. Researchers with relationships to only one coauthor of a particular group demonstrate better scientific performance than researchers with relationships to many coauthors within a group of linked coauthors.

In this subsection, we investigate the collaboration effect in scientific publishing. We selected the following indicators to measure different aspects of scientific collaboration:

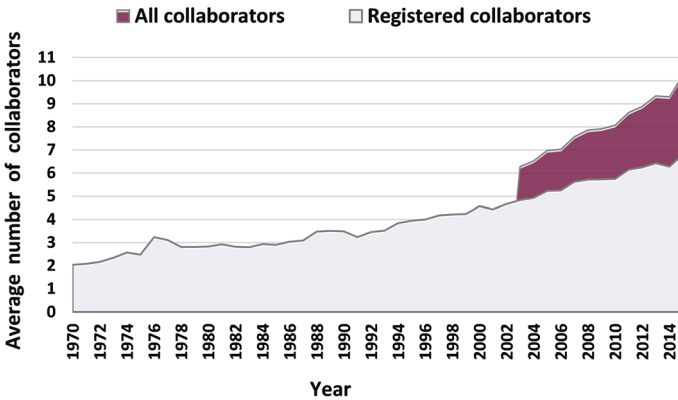
- *The average number of (registered) coauthors per publication* per year. For each year  $y$  we calculate the number of all (and of registered only) coauthors for all publications from  $P_y$  and divide it by the number of publications in the year  $y$ . Both indicators are visualized in Fig. 8.
- *The relative number of solo publications* per year. For each year  $y$  we calculate the percentage of publications from  $P_y$  having only one registered author (see Fig. 9).
- *The average number of (registered) collaborators* for productive researchers per year. For each year  $y$  and each productive researcher  $r$  we calculate the number of all registered researchers that coauthored at least one publication with  $r$  in the year  $y$  and average these numbers over all productive researchers ( $A_y$ ). We also calculate for each productive researcher the number of all distinct coauthors (not only from  $A$ ) and average it over  $A_y$ . We report the second indicator only for the period 2003–2015 (due to CONOR database), see Fig. 10.
- *The average weight of the edges* per year. For each year  $y$ , we compute the average weights of the edges in  $\mathcal{N}_y^{r-r}$ , i.e., obtaining the average number of joint publications between pairs of connected researchers in  $\mathcal{N}_y^{r-r}$  (see Fig. 11).
- *The average fractional weight of the edges* per year. We call the fractional weight of the edges the indicator defined by Newman (2004). Let  $r_1$  and  $r_2$  be two researchers in



**Fig. 8** The average number of coauthors per publication has doubled in the considered period. The average number of registered coauthors per publication is increasing with approximately the same rate. (Color figure online)



**Fig. 9** The relative number of publications with only one registered coauthor is decreasing and falls below one half in 2008

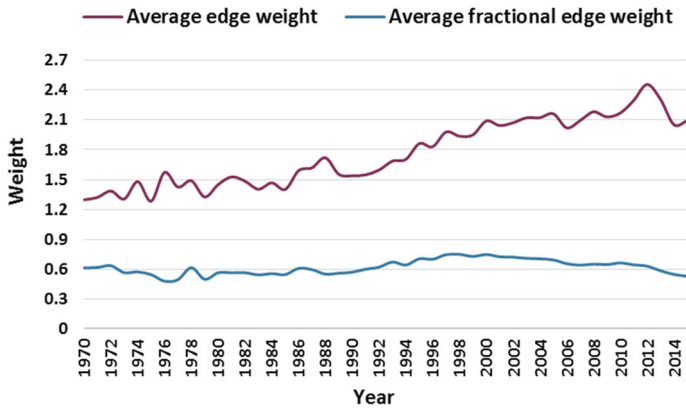


**Fig. 10** The average number of registered collaborators increased from 2 in 1970 to almost 7 in 2015. From 2003, the number of foreign collaborators is also available and in average the order of yearly collaboration network of a researcher is more than 10. (Color figure online)

$\mathcal{N}_y^{r-r}$ . The fractional weight,  $w_y^f(r_1, r_2)$ , of the edge between  $r_1$  and  $r_2$  in the year  $y$  is then defined as

$$w_y^f(r_1, r_2) = \sum_{p \in P_y(r_1, r_2)} (\text{aut}(p) - 1)^{-1},$$

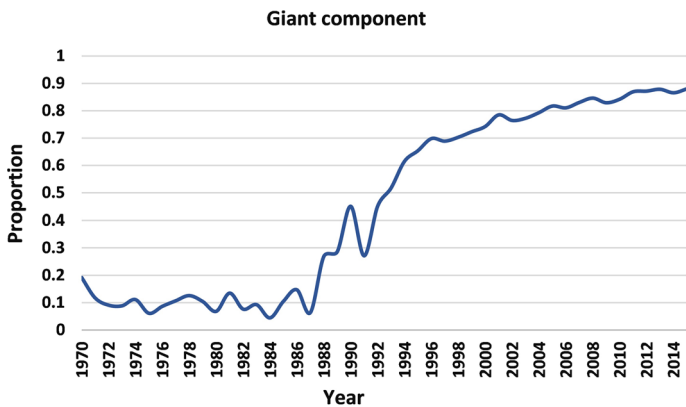
where by  $P_y(r_1, r_2)$  we denote the set of publications coauthored by  $r_1$  and  $r_2$  in the year  $y$ . Recall that  $\text{aut}(p)$  denotes the number of all authors of the publication  $p$ , i.e., also non-registered. The fractional weight of an edge was introduced to provide a measure of interaction between the publication coauthors, where the interaction is assumed to be equally divided among the collaborators. In this sense, we believe that all the authors must be included and hence the use of  $\text{aut}(p)$ . In Fig. 11, it is shown how this indicator evolves in years.



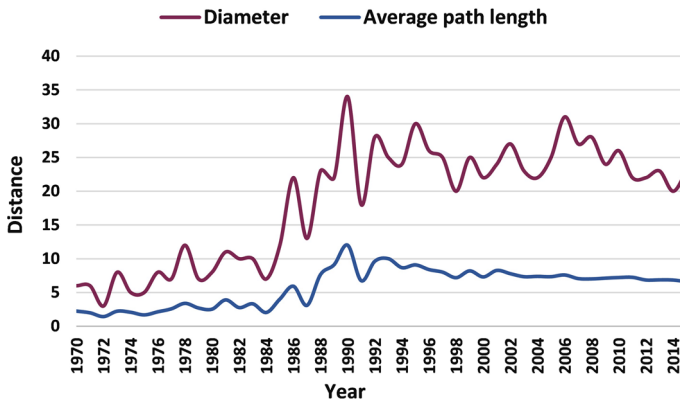
**Fig. 11** In the chart, the average edge weights and the average fractional edge weights in the considered time span are presented. (Color figure online)

We also report the giant component size, characteristic path length, diameter and average clustering coefficient for each of the collaboration networks  $\mathcal{N}_y^{r-r}$  for the time span 1970–2015, as previously defined in “Data and methodology description” section (Figs. 12, 13, 14).

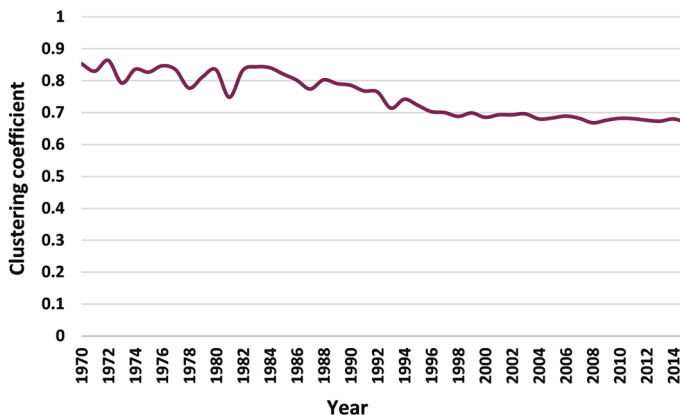
All three diagrams from Figs. 8, 9 and 10 demonstrate that all presented indicators of collaboration show increment of collaboration almost through the whole time span. The difference between the two diagrams in Fig. 8 is mainly due to collaboration with researchers outside Slovenia. In the year 2015 each publication had on average about 3.3 coauthors and on average 2.2 out of them were registered researchers (i.e., almost surely affiliated in Slovenia). The relative number of solo publications (see Fig. 9) is decreasing, which also means that more and more publications have more than one registered author. This finding may be related to the fact that coauthored work results from funded research projects where multiple researchers are involved (Fox and Mohapatra 2007). Relatively high numbers (e.g., since 2008 it is below 0.50) show that there is still high share of publications having only one registered (i.e., affiliated in Slovenia) coauthor which means that collaboration within Slovenia has lots of possibility to grow.



**Fig. 12** The size of giant component in collaboration networks reaches 88% in 2015



**Fig. 13** The diameter of the networks is fluctuating in whole time period, while the average shortest path length is slowly decreasing and stabilizes at 6.6. (Color figure online)



**Fig. 14** The average clustering coefficients are slightly decreasing from early 1980s, but remain on a high level all the time

From Fig. 10 we can conclude that every registered researcher had written in 2015 her publications on average with around 10.2 coauthors and approximately 6.7 out of them were registered in Slovenia. Regarding the two indicators of edge weights represented in Fig. 11, one can observe the growth (although only a slight one in the last two decades) of the former until 2012. The drop in the years 2013–2015 is evident. The latter indicator, the average fractional weight of the edges, is less monotone, but still fairly constant.

Figures 12, 13 and 14 additionally highlight the dynamics in collaboration of Slovenian research community. The relative sizes of giant components (see Fig. 12) have big variations before the year 1995 and afterwards started monotonically increasing. This means that more and more researchers are connected based on their yearly productivity. In 2015 it reached the value of 88% which means that for 88% of active researchers in 2015 there exists a path connecting them. The average length of these paths is also decreasing from early 1990 s on and in 2015 there exists on average a path of length 6.6 between any pair of active researchers from the giant component. However, the diameters of collaboration networks are very fluctuating in whole time period. The main reason behind this is that all



the time new researchers from different research fields start collaborating and when there appears a link between two big and unconnected groups this pushes the diameter up.

The average clustering coefficients  $C_y$  are slightly decreasing from early 1980s, but stay on high level all the time (in 2015  $C_{2015}$  is equal to 0.67, while the average clustering coefficient of the giant component is equal to 0.66). Joining non-connected groups into connected, which is a side effect of the giant components growth, in general decreases average clustering coefficient. High values of  $C_y$  show that the ego-(sub)networks in 1-mode networks  $\mathcal{N}_y^{r-r}$  are very dense and small. For an illustration, in the year 2015 there were 2743 researchers with clustering coefficient greater than 0.8, but 77% of them had at most 4 coauthors. The most collaborating researchers (i.e., those having at least 30 different coauthors) have small clustering coefficient (e.g., in 2015 there were 124 such researchers with average clustering coefficient 0.27). We confirmed this fact by computing the correlation between the clustering coefficients and the weighted degrees of researchers. There is a fairly strong negative correlation (around  $-0.60$ ) until the year 2004, when it increases and fluctuates between  $-0.55$  and  $-0.50$  until 2010. In the last five years, the correlation is weaker (around  $-0.40$ ), and even approx.  $-0.20$  in the year 2012. Although the correlation is decreasing, we can still conclude that having many coauthors results in lower collaboration between them.

Figures 8, 9, 10, 11, 12, 13 and 14 show that the observed indicators of collaboration were quite unstable for the period up to 1991 and afterwards have stabilized and demonstrate steady improvements. Economic crisis did not affect significantly these indicators so we conclude that the stable political system, including the state research policy is a framework that enables better and better collaboration among researchers.

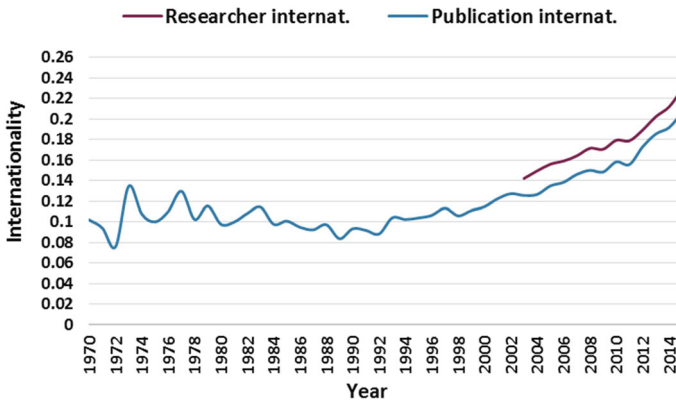
Note that the previously described characteristics of the Slovenian coauthorship networks have already been identified by Perc (2010a) for the time span 1960–2010.

## Internationality

Current review of literature shows that previous studies mainly focused on productivity on a country level. However, research collaboration at the international level is growing (Glänzel 2001). Wagner (2002) showed that public support for research has grown, making potentials for a larger number of worldwide collaborations. For example, the European commission initializes a European Research Area to stimulate research collaboration between different members. Empirical evidence reveals that multinational papers are cited twice as frequently as papers by authors from a single country or institution (Narin et al. 1991; Glänzel and Schubert 2005). Leydesdorff et al. (2013) show that in the past collaborative work was dominated by a few European countries and USA, while today it involves a much larger core of countries. Han et al. (2014) observed that country collaboration networks have reached a certain degree of maturity, while international collaboration networks are still evolving and are made up of multiple components.

Collaboration with foreign researchers is an important aspect of research work, especially in a small country like Slovenia. Performing research in a wider community enables generation of new ideas and improves performance of an individual researcher. In this subsection we consider this aspect. We propose two indicators to measure the internationality.

- *Publication internationality*: for each publication  $p \in P$  we define its internationality as a ratio between the number of non-registered authors (these are mostly foreign researchers) and the number of all authors of  $p$ . The publication internationality of Slovenian researchers in a year  $y$  is the average of publication internationalities



**Fig. 15** The charts represent the average publication internationality (blue), and the average researcher interdisciplinarity (red). The publication internationality varies a lot in the first two decades and starts with stable growth in 1992. The researcher internationality also grew in the period 2003–2015. (Color figure online)

computed over all publications published in this year. See Fig. 15 for visualization of this indicator over the time.

- *Researcher internationality*: for each registered researcher  $r$  we define her internationality as the quotient of non-registered (i.e., in most cases foreign) coauthors of her publications in the year  $y$  and the total number of coauthors in the same year. Due to incomplete data we compute this indicator only from 2003 on. For each year  $y$  we compute the average of researcher internationalities of all productive researchers in this year and visualize it in Fig. 15.

The blue diagram in Fig. 15 shows that the publication internationality varies a lot in the first two decades and starts with stable growth in 1992. The fluctuations up to 1990 are mainly due to unstable political environment in Slovenia in this time and that the COBISS database started only in 1991. The publication internationality grew faster in the last period (after the year 2011) and finally reached the value of 0.21 in 2015 which means that each publication published in this year had about 21% of foreign coauthors on average.

The red diagram in Fig. 15 reveals that the researcher internationality also grew in the period 2003–2015. Every active researcher had in the year 2003 on average 14% of coauthors outside Slovenia and this share has almost doubled until 2015 (23.4%). We believe that important historical milestones like joining NATO and EU and increasing importance of EU research funding had positive impact on Slovenian internationality, observed in Fig. 15. In the last decade Slovenia also started with a stronger financial support for international cooperation by funding the bilateral projects with neighboring and priority countries. However, as demonstrated in “[Determinants correlations](#)” section the higher internationality does not necessary mean higher productivity.

## Interdisciplinarity

Interdisciplinary research is more frequent in applied disciplines while disciplinary collaboration occurs more in basic disciplines (Van Rijnsoever and Hessels 2011). Liu and Xia (2015) examine the structural properties and evolutionary patterns of interdisciplinary coauthorship networks. First, they found that coauthorship network gradually evolves into

a core-periphery structure. Second, with the respect of giant component, they found three stages in the evolution of the coauthorship network: giant component has gradually grown from a small clusters towards modular structure and has finally evolved into a small world. Third, they demonstrate that in the small world stage the giant component contains a hierarchical structure. Upper level of the hierarchy is comprised of a small proportion of highly connected authors and the lower level contains the majority of authors with small number of coauthors.

Interdisciplinary and multidisciplinary of research has been ignored in the two recent important strategic documents of Republic of Slovenia: Slovenia’s Development Strategy<sup>10</sup> and Resolution on Research and Innovation Strategy of Slovenia 2011–2020.<sup>11</sup> However, cooperation and two-way knowledge exchange with non-academic sectors is strongly emphasized in both documents (and also stimulated by instruments that followed both documents). We believe that these instruments had positive impact also on inter- and multidisciplinary of research.

We rely on the measures for the interdisciplinarity introduced in Lužar et al. (2014) and use the classification vectors that we can assign to every registered researcher  $r$  (see “Data and methodology description” section). We propose to measure interdisciplinarity of Slovenian researchers using two indicators, computed on 2-mode networks  $\mathcal{N}_y^{p-r}$ :

- *Publication interdisciplinarity* for a given publication  $p$  is defined as

$$\text{idis}(p) = \sqrt{\frac{6}{5}} \sqrt{1 - \|\text{class}(p)\|^2},$$

where  $\text{class}(p)$  is the centroid of classification vectors for the registered authors of  $p$ :

$$\text{class}(p) = |N(p)|^{-1} \sum_{r \in N(p)} \text{class}(r).$$

The average of  $\text{idis}(p)$  is computed over all publications from each year and visualized in Fig. 16.

- *Researcher interdisciplinarity* for a given registered researcher  $r$  in the year  $y$  is computed from the centroid of classification vectors of her registered coauthors (we denote it by  $\text{class}(r)_y$ ) in the same year using the same formula as above:

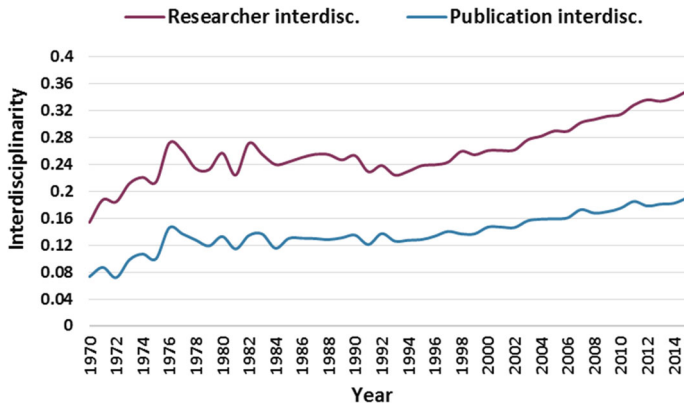
$$\text{idis}_y(r) = \sqrt{\frac{6}{5}} \sqrt{1 - \|\text{class}(r)_y\|^2}.$$

In Fig. 16, the average values  $\text{idis}_y(r)$  computed over the set of all productive researchers  $A_y$  are presented.

We can observe from Fig. 16 that after the turbulent period in the years up to the year 1990 both indicators stabilize and start growing from 1993 on. We can see that researchers interdisciplinarity is always higher than publication interdisciplinarity, which means that researchers often collaborate and publish with researchers from other disciplines but on each publication (and therefore on the project behind) the interdisciplinarity is lower.

<sup>10</sup> <http://www.arrs.gov.si/en/agencija/inc/ssd-new.pdf>.

<sup>11</sup> [http://www.arhiv.mvzt.gov.si/fileadmin/mvzt.gov.si/pageuploads/pdf/odnosi\\_z\\_javnostmi/01.06.2011\\_dalje/01.06\\_RISSdz\\_ENG.pdf](http://www.arhiv.mvzt.gov.si/fileadmin/mvzt.gov.si/pageuploads/pdf/odnosi_z_javnostmi/01.06.2011_dalje/01.06_RISSdz_ENG.pdf).



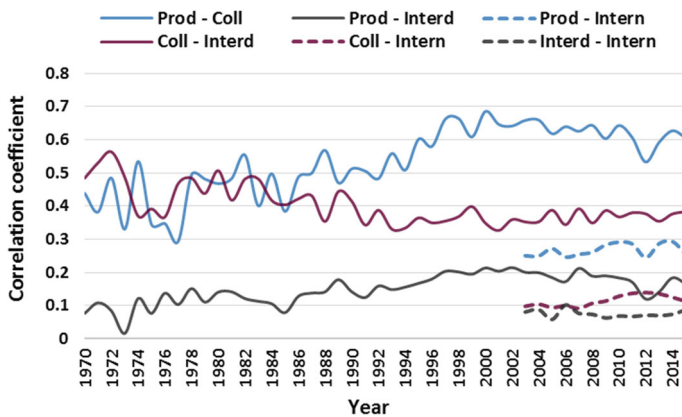
**Fig. 16** The charts represent the average publication interdisciplinarity (*blue*), and the average researcher interdisciplinarity (*red*). The average publication interdisciplinarity stabilizes around 1990 and starts to grow reaching 0.2 in 2015, whereas the average researcher interdisciplinarity also fluctuates before 1990 and starts to grow after. It is almost twice higher as the average publication interdisciplinarity in every year. (Color figure online)

Similar pattern is observed worldwide (Leahey et al. 2016). The growth of both parameters is particularly interesting, since Lužar et al. (2014) concluded that the interdisciplinarity is stable or even slowly decreasing within the communities one can detect in coauthorship networks. This difference, between the trends in communities and in ego-networks, is perhaps worth of an independent investigation.

## Determinants correlations

In this subsection, we study how the selected four determinants of research performance correlate between each other. We computed Pearson's correlation coefficients for all six pairs of four indicators (number of researchers' publications, number of researchers' coauthors, researcher internationalities, and researcher interdisciplinarity) for every year of the studied interval. Notice that each of the four selected indicators is computed for every researcher (in the case of interdisciplinarity, for every researcher classified in at least one of the first six branches). For each indicator, we computed a vector of the values and used it to compute Pearson's correlation coefficients. The values of six coefficients over the years are represented in Fig. 17.

We can see that the correlation between productivity and collaboration is high, more than 0.6 since 1997, meaning that high productivity implies also high degree of collaboration. On the other hand, the correlations between productivity and interdisciplinarity (below 0.2), and between productivity and internationality (below 0.3) are much lower. The correlation between collaboration and interdisciplinarity is almost 0.4, which shows that more interdisciplinary researchers collaborate more. The remaining two pairs, collaboration and internationality, and interdisciplinarity and internationality are almost not correlated.



**Fig. 17** The Pearson’s correlation coefficients for six pairs of indicators are presented. The correlations, where one of the indicators is the researcher internationality, are presented only from the year 2003. (Color figure online)

### Conclusions

In this paper we analyzed the productivity, collaboration, internationality, and interdisciplinarity of Slovenian researchers in the time period 1970–2015. For each criterion we selected some known or defined our own indicators and measured them based on high quality data from two well-maintained information systems, namely COBISS and SiCRIS.

We demonstrated that scientific productivity has started increasing fast after the year 1992, soon after Slovenia won independence from Yugoslavia. The productivity reached the peak in 2011 and started declining afterwards. The average number of publications per author has increased a lot in the period 1990–2010 and has stabilized in the years 2011–2015. This is mainly the consequence of more competitive atmosphere in Slovenia due to political and societal changes in 1990s.

We consider the average fractional number of publications per researcher as the most appropriate measure for the real personal scientific productivity. This indicator is not varying a lot. It was increasing in 1990s, was stable in the following decade and started declining from 2011 on.

Regarding productivity, we used a concept of the career productivity. We demonstrated that the number of active and productive researchers is fastly decreasing over career time span. However, those who remained active were increasing their productivity until the end of average academic career (i.e., about 35 years after PhD). It is interesting that there are still 51 registered researchers who have been active since 1970 and have published in 2015 in total 259 scientific publications.

The collaboration of Slovenian researchers was assessed using three indicators: (1) the average number of coauthors per publication per year, (2) the relative number of solo SiCRIS publications per year, and (3) the average number of collaborators of registered researchers. All these indicators demonstrate almost monotonic increasing of collaboration in the time interval 1970–2015.

Collaboration was additionally quantified by computing giant components, characteristic path lengths, diameters and clustering coefficients of the 1-mode networks  $\mathcal{N}_y^{r-r}$ . They all stabilize in 1990 s and confirm that the collaboration among registered researchers is increasing with time.

We measured the internationality of the Slovenian research community through the publication internationality and the researcher internationality. Both measures show that internationality is also monotonically increasing since the beginning of 1990s.

Finally we evaluated the interdisciplinarity of Slovenian researchers in the period 1970–2015. We proposed to measure publication interdisciplinarity and researcher interdisciplinarity. The analysis showed that after the turbulent period in years up to the year 1990 both indicators have stabilized and have started growing from 1993 on. The researchers interdisciplinarity is always higher than publication interdisciplinarity which means that researcher often collaborate and publish with researchers from other disciplines but each particular publications include mostly coauthors from one or two disciplines.

To sum up, the main conclusion is that the historical milestones have reflection in the performance of the research community. In particular, political and financial instability have always had (mostly negative) impact, while positive innovations like deployments of COBISS and SiCRIS databases and stable environment positively stimulate researchers.

**Acknowledgements** The authors thank two anonymous referees for their remarks which helped to improve the manuscript. This research was supported by Slovenian Research Agency Program P1–0383.

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