Profiling giants: The networks and influence of Buchanan and Tullock

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Abstract:
This paper uses network analysis to measure the positions and influences of two prominent academics, James M. Buchanan and Gordon Tullock, founders of public choice theory. First, we recount parallel accounts of their lives. Second, we provide a literature review and outline the standard centrality measures insisting on their relevance in assessing the two authors' roles in a given network. Third, we analyze their respective influences through the lens of network analysis by providing details on the publication records and, overall, co-authorship networks of the two scholars. We also explore their academic genealogy and show in particular that (i) Buchanan and Tullock's careers followed parallel paths and co-founded public choice theory and the journal of the same name, although the two had few common works; (ii) though being apparently very similar as to their centrality in the co-authoring network under scrutiny, their ego-networks were structured very differently, revealing diverse positions in the field and, thus, different influences on the discipline.

Keywords: Buchanan, Tullock, Networks, Co-authorship, Dissertation students, Influence, Public Choice.

JEL Classification: A14; D85; I23

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1. Introduction

Although it is recognized that the birth and development of public choice as a legitimate field of economic analysis largely can be traced to James M. Buchanan (1919–2013) and Gordon Tullock's (1922–2014) work and efforts, it probably is less well known that their academic careers have been parallel, if not intertwined. Moreover, given the celebrity and posterity of their common book, *The Calculus of Consent* (Buchanan and Tullock 1962), their collaboration could have been expected to expand to several, even many, articles, chapters, or other books.

Nevertheless, their co-publication record contains only six articles (Buchanan and Tullock 1964, 1965, 1975, 1976b, 1977, 1981)[1] and one book co-edited with Robert Tollison (Buchanan, Tollison, and Tullock 1980), which is a collection of original and reprinted papers. Compared to journal articles, 161 (Buchanan's) and 145 (Tullock's), attached to their names in RePEc[2] (which underestimates the numbers of their published works, as both authors started their careers before the Internet era; and, moreover, as many op-eds, comments and book chapters are not listed by the database), it appears that their collaboration was not as strong as one could have expected (at least in written, published, form).[3] In a nutshell, in spite of almost parallel careers, their publication records were more "orthogonal" than one would have thought.

Naturally, there is more to intellectual collaboration than just publication (Laband and Tollison 2000). Nevertheless, relying on publications and citations to study academic colleagues simply assumes a specific form of scientific acquaintance and has the advantage of relying on "successful" (and measurable) collaboration (and even more so if several publications are co-authored). The objective we pursue in this paper is to analyze how Buchanan and Tullock's impact grew out of their direct collaboration and of the larger influence in the public choice field. We do so by a careful inspection of their respective and individual co-authorship networks. That approach allows us to uncover how the founders of public choice theory disseminated their ideas

[1] The count goes up to seven when taking into account a reply to a comment; see Buchanan and Tullock (1976a).
2 RePEc stands for Research Papers in Economics. The depository can be accessed at the following URL: repec.org. For a description of the rankings derived from RePEc see, e.g., Zimmermann (2013). The count here excludes reviews of books.
[3] It appears that the archives reveal that Buchanan and Tullock put together a NSF proposal for a project, under the heading "The Calculus of Control", on which they collaborated and of which they laid out various parts and pieces. In retrospect, while they never published that volume, they published all of its various constituent parts in various separate works. It is thus probable that they had many discussions, which did not end in joint publications. We owe this point to a referee.

through academia, from the beginnings of their respective careers up to the most recent publications (including papers that may have been published after their respective deaths). It also allows us to reveal how public choice spread through the economics discipline and beyond, by detailing the ways in which the networks of their direct, as well as indirect, collaborators were structured. Then, we add to this a network analysis of Buchanan and Tullock's Ph.D. students with whom they published (thus providing a genealogical tree of their academic children and grandchildren).

The paper hence not only pays tribute to the two giants of public choice, but also shows how network analysis can fruitfully be used both to reveal and analyze patterns in scientific (sub-) disciplines, and to study academic influence, thus contributing to the literature on co-authorship. With regard to the latter, our analysis details the types of pattern among star economists, such as the one exhibited by Goyal et al. (2006), by focusing on public choice's co-founders. The literature on co-authorship has explored the returns to co-authorship between scholars with asymmetric backgrounds, showing that the benefits of collaboration accrue more to the senior than to the junior academic partner (see e.g., Abbasi et al. 2011; Besancenot et al. 2017; Bidault and Hildebrand 2014).

In our case, however, it would be hard or rather irrelevant to define one or the other founder of public choice as a junior partner, although the positions of their co-authors is a more open question. Hollis (2001) and Ductor et al. (2014) have investigated co-authorships, too, and in particular how much knowledge about an author's network can improve forecasts of her individual output. Their analysis reveals that a network has predictive content, although the latter shows that the impact dissipates over time. Here, we uncover the internal structures of the two giants' collaborator and student co-authorship networks. Hence, while Azoulay et al. (2010) look at the impact of the "death of a superstar" on their co-authors' productivities, we here analyze how the journal publication networks of two public choice superstars are organized. We thus do not provide a predictive analysis but instead underscore how different though seemingly close to each other Buchanan and Tullock's networks were and, as a consequence, how complementary they have been in structuring and developing public choice analysis.

It should be mentioned that we do not assess whether Buchanan and Tullock voluntarily structured their networks and collaborations in the way our analysis unearths it. Although the biographical sketch we provide in the first part of the paper highlights the fact that their lives followed almost

parallel paths, it does this from the present perspective, with the benefit of hindsight. By definition, it thus falls short of analyzing the determinants of the choices that lay beyond the decisions that underpinned the parallelism. We have to leave that for their biographers, and can only hope that this paper may be useful to them.

The remainder of the paper is organized as follows: first, we describe the (parallel) careers and (not-so parallel) works of Buchanan and Tullock. Then we discuss the relevance of the literature on academic networks to assess researchers' productivities and long-lasting influences. Relying on that background, we investigate Buchanan and Tullock's respective influences, through their direct and indirect co-authors and dissertation students. The final section concludes the paper.

2. Buchanan and Tullock: parallel careers, with few common works

Interestingly, in the 1998 foreword to the online version of *The Calculus of Consent*,[4] Buchanan presents Tullock as one of "colleagues" and his colleagues as "co-authors, co-entrepreneurs in academic enterprises, and co-participants in an ongoing discussion." The preface, signed by both, distinguishes the contributions to the book by name in a manner that is not usual in present-day economics.[5] Those pages more than hint at the possibility that, although they went through what can be considered as parallel professional lives, their positions in the development of public choice, and thus their way of working, were not as parallel as it seems. In a nutshell, they appear to have been more complementary than substitutable, an attribute we delve upon in this section.[6]

2.1.1. Trajectories

Given the intrinsic limitations of a journal article, we cannot pretend comprehensively to summarize the biographies of Buchanan and Tullock.[7] Nevertheless, a brief account of their

[4] Available at the following URL: http://files.libertyfund.org/files/1063/Buchanan_0102-03_EBk_v6.0.pdf (last consulted, 12 February 2017).
[5] Compared to the medical sciences or physics, for example, where contributions are more often decomposed and attributed explicitly.
[6] That conclusion is also apparent if one reads the separately signed appendices to the Calculus: Buchanan was more of a political philosopher and Tullock more of an economist/game theorist - in 1962, at least.
[7] Some information is now available on the Internet, and historians of economic thought can take a much deeper dive into the connections between the two than we can intend to do here.

careers reveals that they had many opportunities to realize even more joint works than they took advantage of.

Being the older of the two, Buchanan (1919–2013) graduated first from Middle Tennessee State University in 1940. After WWII, he earned a Ph.D. from the University of Chicago in 1948. He joined the University of Virginia in 1956, where he stayed until 1968, before leaving to work at UCLA for one year. He then joined the Virginia Polytechnic Institute & State University (now Virginia Tech), where he stayed for a relatively long period (1969 to 1983). A conflict with its management caused him to leave, and he moved at the same time as Tullock (1922–2014) to George Mason University, where he stayed until his official retirement in 2007, and where he was the sole winner of 1986's Nobel Prize Economic Sciences ("for his development of the contractual and constitutional bases for the theory of economic and political decision-making," according to the Nobel Committee – see Atkinson 1987).

Tullock moved to George Mason in 1983, a little before inviting Buchanan to join him the same year. He stayed there until 1987, and then left for the University of Arizona (from 1987 to 1999), before coming back to George Mason (in both the economics department and the School of Law) in 1998, where he stayed until his own official retirement, in 2008 (see Parisi et al. 2017). Before pursuing an academic path, Tullock had worked for the US Foreign Service, and his first stint in academia was as a Postdoctoral Fellow, in 1958–1959, at the University of Virginia, where Buchanan had been working since 1956. He then moved on to University of South Carolina and Rice University before returning the University of Virginia in 1962. In 1968, he moved to Virginia Tech, with Buchanan joining him one year later. In fact, that Tullock moved there first was part of the lure for Buchanan to come to Blacksburg from UCLA and to build their new center at that institution.

The routes of Buchanan and Tullock through academia thus were intertwined, almost parallel, as they had worked as colleagues for 31 years in the same institution(s). Their co-entrepreneurship resulted in the founding of the Center for Study of Public Choice (1969) and, of course, in the establishment of the journal *Public Choice* (first titled *Papers in Non-Market Decision Making*). However, their co-authorships, as described above, were neither as extensive as could be expected nor as intense as many believe, even though the two names were more often than not associated with each other. That is not meant to discard the respective contributions both brought to economics, but when we look at the citations of their work in *Public Choice*, as extracted from the

RePEc database, it appears that Tullock receives 1,041 citations, while Buchanan gets 1,472 citations.[8] However, if more than half of those citations refer to their common works, half of these go to *The Calculus of Consent*. To state the fact differently, the six journal articles they co-authored account for less than 5% of their respective publication records.

2.2. Works: publicizing or developing public choice analysis

Buchanan delivered a total of 232 academic articles (of which 161 are listed in the RePEc database), published in 83 journals. However, eight journals gather more than 43% of the total (by declining numbers of publications: *Public Choice*, *American Economic Review*, *Cato Journal*, *Journal of Political Economy*, *Constitutional Political Economy*, *Kyklos*, *Southern Economic Journal*, and *National Tax Journal*). For Tullock, the count delivers 167 academic articles (of which 145 are listed in RePEc) in 53 journals. Tullock has a more concentrated profile, since more than 49% of his papers were published in six journals only (*Public Choice*, *American Economic Review*, *Journal of Political Economy*, *Kyklos*, *Journal of Money, Credit and Banking*, and *Atlantic Economic Journal*). Also, Buchanan collects 54 "one-shot" journals (i.e., outlets where he and his possible co-authors published only one paper), which represent about 23% of his articles, against 27 and about 16%, respectively, for Tullock. More formally, the Herfindahl-Hirschman indices[9] of both authors are, respectively, 358 for Buchanan and 877 for Tullock, confirming the higher concentration of the latter's journal articles.

Another perspective comes from observation of the journals that both authors used to convey their ideas and research results. As said before, Buchanan published in 83 different journals, of which 26 are shared with Tullock. Tullock's papers were published in 53 journals. A look at the non-common journals reveals an interesting pattern: more than a quarter of the journals in which Buchanan published (but not Tullock) are not economics journals but serve as outlets for other disciplines (such as political science, sociology, philosophy, science and human resources) or are at the borders of two or more disciplines (as with the *American Journal of Economics and Sociology*, *Rationality, Markets and Morals* or *The Canadian Journal of Economics and Political*

[8] Compilation realized in March 2017.

[9] Formally, HHI = $s_1^2 + s_2^2 + \cdots + s_n^2$, where n is the total number of journals ranked by decreasing order and s_i denotes the share of the ith journal. HHI lies in the [0,1] interval. Larger values of the index indicate that the author's publications are more concentrated within the n journals.

Science).[10] On the other hand, of the 27 different (with regard to Buchanan's) journals where Tullock published, 11 could be characterized as field journals in economics (e.g., *Journal of Human Resources, Defense and Peace Economics, The Journal of Bioeconomics*), while some are in disciplines other than economics (*American Political Science Review, American Naturalist, Perspectives on Politics, Bulletin of the Ecological Society of America, The China Quarterly, and so on*).

All in all, the above analysis suggests that Buchanan publicized public choice methods more widely, opening it to other disciplines, while Tullock's approach appeared to be more concentrated on disseminating public choice methods in various fields of economics. Interestingly, in his note on "Nobelity," Buchanan admits that he did not want to be considered as "an 'instant expert' on everything" because of the Nobel Prize, though he appreciated opportunities to promulgate "constitutionalist ideas" he deemed important for any citizen (Buchanan 2001).[11] While Tullock came to work as a professor in the economics department, he also had an appointment in the School of Law at George Mason and, while he had first been trained as a lawyer, he kept on "deduc[ing] legal principles that were not based on ethics or morality, but rather deduced from a framework of Pareto optimality" (Parisi et al. 2017, p. 51).

To summarize our point, it appears that the two giants we consider here had co-authored much less material than presumably thought. We now turn to investigate whether absence of co-authorship means that their networks of co-authors were completely distinct.

3. Assessing influence through centrality and connectivity measures

This section first sketches the results of network analysis and describes the standard measures of what being "central" in a network means. It then considers the interrelations of those measures, as well as different dimensions of a network each of them discloses.

[10] Fourcade et al. (2015) document the parochialism of the economics discipline relative to other social sciences. Buchanan certainly was different from other American economists, as his track record (as well as his publication record) reveals connections with other disciplines, sometimes far from economics. That is less true for Tullock.

[11] Not that we would hint that any of the two authors considered here has consciously aimed at such an influence throughout his life, especially so as we look at their networks in hindsight. See, again, Buchanan's "Notes on Nobelity" (Buchanan 2001), where he admits that he has financially benefited from the celebrity status associated with the Nobel Prize – although probably much less than he could have, had he accepted all of the invitations based only on his sudden notoriety —but has refused to become a columnist on all and every issue.

3.1. What we can learn from network analysis

According to Newman (2001, p. 404), "a social network is a collection of people, each of whom is acquainted with some subset of the others. Such a network can be represented as a set of points (or vertices) denoting people, joined in pairs by lines (or edges) denoting acquaintance. One could, in principle, construct the social network for a company or firm, for a school or university, or for any other community up to and including the entire world."

Academic network analysis, first fuelled in the 1970s by the development of network analysis, and, thereafter, by scientometrics, is now established as an independent specialty. Every discipline develops inward-looking insights into its structuration and progress. Of course, advances in computing, databases, and web-searching engines allow us to gather and analyze large volumes of data, making it possible to uncover even better the generic properties of networks.

A large part of the effort has been focused on co-authorship networks as a form of social network. Since intellectual collaboration is probably multi-dimensional (Laband and Tollison 2000), it is now commonly accepted to rely on publications and citations for studying academic collaborations, as such reliance simply assumes that co-authoring a paper relies on a form of scientific acquaintance (as Newman 2001, p. 404, states: "most people who have written a paper together will know one another quite well"). Moreover, a common publication record is an indicator of "successful" (and measurable) collaboration (and even more so if several publications are co-authored). Co-authorship networks thus have been studied thoroughly in many disciplines (see, as a paradigmatic example, Newman's 2001 work on biomedical, physics, and computer science research). That is not only because co-authoring a paper signals real acquaintance (as opposed to a random encounter) or because of unhealthy curiosity, but also because the structure of co-author networks has important implications for the spread of information and therefore is of scholarly (and potentially policy) interest. Such interest is explained by the fact that the number of acquaintances, for example, may signal individuals who might substantially influence the work of others and thus disseminate new ideas, methods, or results.

The analysis of the structure of a network thus is of obvious importance. As stated by Yin et al. (2006), a network can be characterized by what can be referred to as its macro-level network properties, defining the overall "performance" of the network itself, given its structural attributes.

Performance or efficiency will arise whatever the level of consciousness the members of the network may have of its structure. Correspondingly, a network also embodies micro-level properties, which may influence the behavior of its members, as they confront the network's differential constraints, opportunities, or both. Those micro-level properties then reflect, as much as they mold, the "power" of each individual belonging to the network (once he/she has connected to it). That power is the "social multiplier effect" of networks (Dolton 2017, p. 2). Hence, networks generate as much as they modify the positive and (sometimes) negative spillovers among their members (as each member's performance is determined partly by the contributions of other members, conditionally on her position in the network) and, by way of consequence, knowledge of the network structure may influence and change its members' behaviors in strategic ways. Therefore, positions in the network structure must be measured, and one can rely on several "centrality" metrics that aim at revealing and precisely assessing the relative clouts of all of the network's members. In other words, if a graphical description of a co-authorship network can reveal its apparent structure, the application of centrality measures can unveil more of its hidden, and more structuring, dimensions.

Of course, a literature dedicated to the analysis of co-authorship networks in economics now exists. That literature has been able to show that the discipline is indeed a "small world", especially since the distance between all authors in economics declined between 1970 and 2000 (Goyal et al. 2006). More interestingly for what concerns us here, Goyal et al. (2006) show that economics' shrinking world is explained by the structure of the discipline's network, in which "stars" (i.e., authors with many collaborators who often do not work together) are interlinked. Also, the results of Bidault and Hildenbrand (2014, p. 1011) illustrate that the gains from co-authorship are "associated with one's own competences, and with the quality of relationship obtained from past academic interactions with the same co-author", and that junior partners in a co-authorship relation benefit strongly from interactions with more senior colleagues, a result similar to that of Abbasi et al. (2011), or Besancenot et al. (2017). Such asymmetries in gains from collaboration can be considered to be a rejoinder to Hollis's (2001) finding of apparently decreasing returns to scale from co-authorship.

We, however, do not yet know much about the influence of public choice, from its founders to broader audiences. Public choice itself started from the fringes of the existing economics discipline (rejecting "all of the pillars of the Samuelsonian revolution", according to Boettke and Marciano 2015, p. 54). The future of public choice obviously is hard to ascertain, except for

repeating Ostrom's (1993, p. 163) words (published almost 30 years after *The Calculus of Consent*, in the 25th birthday issue of the journal reflecting on the prospect for the next 25 years), as he states that "the most important potentials are associated with diverse thrusts on the peripheries of work in the public-choice tradition rather than at the core of applying 'economic' reasoning to non market decision making." Knowing the past and envisioning the future, we focus on the present state of the field, as it can be perceived through the lens of network analysis.

Other authors have looked at the influence of public choice. However, it must first be noted that retracing the influence is not that easy for public choice, as it is not often recognized as an autonomous (sub-)field and therefore has been merged with public finance and/or political economy (for a typical example, see Ellison 2013).[12] Second, the field's influence can be measured by the impact the development of a specific research community has on its immediate environment. For instance, Wagner (2004) studies the relative impact on the three academic institutions in which Buchanan and Tullock developed their research agendas, while Vaughn (2015) detailed how the (final) location of the Public Choice Center profoundly influenced the development of George Mason University.

Third, influence can be considered as one's work having a long-lasting and recurrent effect on the development of subsequent research. That is typically done nowadays by analyzing citation counts. The obvious drawback of that approach is that it induces focus on people instead of considering a field or its methodology.[13] Nevertheless, using such a method and focusing on the citations received by Nobel Prize winners in economics, including those by Boettke et al. (2012), reveal that Buchanan's work is among the most influential ones in terms of its impact on the social sciences, as measured by the annual number of citations received over the 1970–2007 period. However, the relative position of Buchanan erodes slowly from rank 15 to rank 29 (out of 64) when the sample period is restricted (going from 1970–2007 to 1980–2007, see appendix Tables 5 and 6 in Boettke et al. 2012). Concerning Tullock's specific influence, Schram (2016) looks at the impact his work has had on experimental economics. As he concludes, people in this domain "rarely cite Public Choice scholars, but when they do Tullock is amongst the most cited" (Schram 2016, p. 222).

[12] In some ways, such merging is reminiscent of the classification of Mancur Olson's 1962 review of *The Calculus of Consent* in the "other disciplines" (Medema 2000, p. 316).

[13] An opposite perspective is given, for example, by Hill (1999), who considers how Christianity is part of public choice (that is, how its main hypotheses with regard to people's behavior, in particular, fit with Christian beliefs).

However, those previous analyses do not reveal the structure of the network linking public choice scholars, and that is precisely something we intend to do in this article.

3.2. Centrality and connectivity measures: definitions

The research question of this study can be summarized by asking, who is the most important person in a network? In many ways, the most important person is the most "central" one. However, if the center of a circle easily can be considered to be its most central point, it is not as easy to assess the centrality in more convoluted geometric shapes. Since a network rarely has a circular shape, several centrality measures have been developed to identify the network's center. In what follows, we will rely on the literature's five common measures, which we first present before assessing how connected are the dimensions of centrality each of them reveals more specifically.

The first measure of author centrality in the co-authorship network is her *degree*, which is the number of her co-authors (called "neighbors" in the general social network analysis literature) at a distance equal to one, hence sharing authorship of the same journal articles. Note that the measure can be standardized, for sake of comparison, by dividing the author's degree by its maximum possible network value, $n - 1$. Degree is not only the most obvious individual measure but also the most straightforward one to find. Intuitively, one can reasonably think that the higher is the author's degree, the more diverse and complementary her co-authors will be, and the greater will be her influence because the author in question is related to a larger fraction of the whole set of authors in the network than anyone else. Alternatively, degree can be interpreted as the amount of time it will take to spread information from one specific author to the rest of them. Applied to co-authoring, the ideas of an author with high closeness centrality will disseminate more rapidly throughout the network by the chain of her direct and indirect collaborations with co-authors. So, degree is often an important and effective measure of influence for a given author.

The second measure of centrality is the degree of *betweenness centrality*, which measures the author's overall "intermediarity" in the formation of co-authorship links. Explicitly, the more "central" are the authors who belong to an ego-network, the more compact each ego-network will

be.[14] Author *i*'s betweenness index is defined by the proportion of all shortest paths (geodesic distances) between any pair of authors that pass through author *i*. Formally, we have

$$C_B(i) = \sum_{j \neq k} \sigma_{jk}(i) / \sigma_{jk},$$

where σ_{jk} is the number of all shortest paths between j and k, and $\sigma_{jk}(i)$ is the number of those shortest paths passing through author *i*. The betweenness values usually are normalized in the case of non-directed graphs by computing factor $2C_B/(n-1)(n-2)$, where $(n-1)(n-2)/2$ represent the number of pairs of authors, except for *i* in an *n*-node graph.[15]

The third metric measures the author's *closeness centrality*, i.e., how close or near an author is to all others in the network. That is done by taking the inverse of the length of the average shortest path between any author, *i*, and all other (reachable) authors in the graph. In other words, the lesser the average number of edges needed for the author to reach them, the closer he/she is to them on average. Hence, we have

$$C_C(i) = 1 / \sum_{j=1}^{n} d(i, j),$$

where $d(i,j)$ is the length of the shortest path between i and j. Usually, this index is normalized as

$$C_C(i) = 1/(n-1) \sum_{j=1}^{n} d(i, j).$$

The fourth measure most commonly used in the network analysis is the author's *clustering coefficient*, which deals not with centrality but with connectivity. It conveys an important property of the social network, transitivity. In the framework of co-authoring, the clustering coefficient refers to the extent to which links between two co-authors are transitive. It is defined, in an undirected network, as the ratio of the number of edges between author *i* and co-authors to the

[14] An ego-network is the network surrounding a particular individual. In other words, it includes the individual surveyed and his or her immediate contacts (Newman 2010, p. 45ff.).

[15] Note that betweenness centrality in citation networks can be interpreted as an indicator of journals' interdisciplinariness (see, e.g., Mutschke 2003; Leydesdorff 2007).

number of connected author pairs between all of author *i*'s co-authors. This measure can be represented as

$$C_{CC}(i) = 2P(i)/N(i)(N(i)-1),$$

where $P(i)$ is the number of co-author links between author *i*'s neighbors, and $N(i)$ is the number of *i*'s neighbors. In a way, clustering delivers a view of the degree of "grouping" of the authors in a network. In other words, an author's clustering coefficient is the probability of two randomly selected co-authors being connected to each other. Hence, dense local clustering in a co-authorship network identifies small cohesive groups of researchers with few collaborating links connecting them (De Stefano et al. 2011). The global clustering coefficient of a network, also called "network transitivity" or, more tellingly, "cliquishness" is the likelihood that any two of an author's co-authors also are connected to each other (Hanneman and Riddle 2011).

According to Ebadi et al. (2015), researchers with high clustering coefficients tend to cluster with other researchers, a feature that results in a tightly knit group of collaborators with a large number of connections among the team members. Ebadi et al. (2015) analyze the tendency to cluster as a strategy for internalizing the "benefits from the tight inter-connections in their groups to produce higher quality works by using the internal referring among the team members."[16] Specifically, any author's clustering coefficient gives interesting insights into her neighborhood, that is, in our context, the author's co-authors' co-authors. Note that, for the author clustering (C_C) measure, a "good score," is a low one, since it translates into the level of interlinking—hence, interlocking—of the neighborhood (i.e., co-authors). In other words, low values of this measure signal that the author is more likely to have diversified collaborations with co-authors who are themselves loosely connected to their own co-authors.

The fifth individual measure is the *Laplacian centrality* of an author *i*. It assesses the impact of deletion or deactivation of that author, everything being equal, on the "Laplacian energy" of the n co-author network G. Formally, consider $D(G) = diag(d_G(1), \dots, d_G(n))$ and $A(G) = (a_{ij})$,

[16] An alternative definition of the global clustering coefficient of an undirected graph is the number of triangles in it (Luce and Perry 1949; Wasserman and Faust 1994). Formally, for a network G:

$$C(G) = \frac{3 \times number\ of\ triangles}{number\ of\ connected\ triplets\ of\ co-authors}.$$

which represent G's diagonal matrix of author degrees and adjacency matrix, with $a_{ii} = 0,\ a_{ij} = 1$ if $ij \in G$ (i.e., i and j are co-authors), and $a_{ij} = 0$ otherwise (i.e., i and j are not co-authors). The Laplacian matrix is then defined by

$$L(G) = D(G) - A(G) = (L_{ij}), \text{ with } L_{ij} = \begin{cases} d_G(i)\ if\ j = i \\ -a_{ij}\ otherwise \end{cases}.$$

Note that the normalized Laplacian matrix is $\hat{L} = I_n - D^{-1/2} \cdot A \cdot D^{-1/2}$. Eigenvalues $\lambda_1,\ \lambda_2,\ldots,$ λ_n of $L(G)$ are obtained by solving $|L(G) - \lambda I_n| = 0$, where λ is a real number, and I_n is the $n \times n$ identity matrix. The "Laplacian energy" of network G is then defined as $E_L(G) = \sum_{i=1}^{n} \lambda_i^2$. Finally, denoting G_i as the network obtained by deleting i from G, Laplacian centrality is given by

$$C_L(i, G) = E_L(G) - E_L(G_i).$$

It can be shown (Qi et al. 2013) that

$$C_L(i, G) = d_G^2(i) + d_G(i) + 2\sum_{k \in N(i)} d_G(k),$$

where $N(i) =$ set of neighbors (co-authors) of i in G. The corresponding relative individual Laplacian centrality index is given by

$$0 \leq \bar{C}_L(i, G) = \frac{[E_L(G) - E_L(G_i)]}{E_L(G)} = \frac{d_G^2(i) + d_G(i) + 2\sum_{k \in N(i)} d_G(k)}{\sum_{j=1}^{n}[d_G^2(j) + d_G(i)]} \leq 1.$$

The importance or influence of a given author on the co-authoring network is then reflected by the magnitude of the decline in Laplacian energy induced by her exit or deactivation from the network and, as an immediate consequence, the severing of the links and the shortest paths passing through her. Laplacian centrality can be shown to be a function of the author's degree plus the degrees of her neighbors, making it an "intermediate measure between global and local characterizations of the position of a vertex in a network. Because of this, we should anticipate that Laplace centrality will reveal differences in network structure that emerge out of significant local influence upon areas in the graph" (Qi et al. 2013, p. 252). Given its complementarity relative to the other centrality measures, it deserves to be used in the analysis of the specific network under the study in this paper.

3.3. Centrality and connectivity measures: relations

Now, we must ask how the standard measures just discussed are related (or not). Although the five centrality measures are used on the same network, they aim at describing it differently (Valente et al. 2008). More precisely, they can reveal different properties, or dimensions, of a given network (Freeman 1979).

Degree centrality is the most basic measure, as it is the sheer number of links a person has within the network. As such, it is the most immediate measure for describing one's position in a network. As for betweenness centrality, it attempts to measure the potential for influencing others, both through direct and indirect "paths." An author with a high degree of betweenness centrality thus is important owing to the possibility of her having to disseminate information throughout the network (Newman 2010). In other words, authors with high degrees of betweenness are the brokers and connectors who bring others together; they have more ability to control the flow of knowledge between most other members. Symmetrically, once they disappear from the network, distances between the remaining members become, on average, longer (Yin et al. 2006). Closeness centrality, instead, measures how efficiently a member of a network can transmit information to other (potentially more peripheral) actors, while Laplacian centrality offers another approach to measuring centrality by, in a way, weighting the information around any author, describing the density of her connections (Qi et al. 2012).

Even though all of the centrality measures obviously are correlated, they nevertheless unveil different dimensions and properties, revealing different aspects of a given position in a network.[17] The researcher's liberty in selecting the most appropriate measure(s) for a given network makes it a subjective choice, but also permits one to devise tailor-made combined measures based on what is effectively sought by analyzing individual and global "centrality" in a specific network. As Qi et al. (2013, p. 252) put it, "As we know, for any particular research project we will have to identify which centrality measure is most meaningful or useful." In our view, however, any single measure would provide an incomplete description. Our interest lies in the fact that, by combining these indicators, one can better describe the position of an author in her network. For instance, an

[17] And, as demonstrated by Schoch et al. (2017), that is even truer if the network differs from stereotypical ones (i.e., stars or circles).

author with a high degree of centrality (that is, having many connections or links) but with a low degree of closeness can be characterized as someone who is embedded in a part of the network, located relatively far from everyone else. The opposite situation (low degree centrality, high closeness centrality) thus characterizes a key broker who is linked tightly to other important brokers. Likewise, an author with a low centrality degree but a high degree of betweenness centrality has few connections, but nevertheless is important in or for the network's structure. Otherwise, an author with a low degree of betweenness, but with a high degree of closeness centrality, is somewhat "redundant" in the network because many other authors have the same position. An author's Laplacian local centrality is based on a quadratic polynomial function of her degree and the sum of her direct co-authors' degrees. Hence, the more numerous is the proportion of her direct co-authors with higher degrees, the more central a given author will be. That centrality concept hence relies on a positive "influence" externality emitted by the (direct) co-authors. It is straightforward to understand why high local clustering tends to reduce the Laplacian measure.

4. Co-authoring with giants (or their co-authors)

In this section, we describe and analyze Buchanan and Tullock's respective centrality and connectivity in the whole co-author network to which they are linked, as well as in their ego-networks. That is done to get hints about how their respective network structures may have contributed to the diffusion of public choice analysis in different fields of economics, thus going further than the analysis of "Non-Market Decision Making" (to refer to the first name of the *Public Choice* journal). It is also done as a way of revealing their relative influences in the network and, by extension, on the public choice field and the economics discipline more generally.

4.1. Morphology of (co-)authors' co-authors networks

We consider the co-author network for journal are articles published by all of Buchanan and Tullock's direct and indirect co-authors until the second degree.[18] The data were compiled by using the RePEc database, completed with JSTOR and the *Public Choice* journal's website for

[18] We chose to limit our analysis to the second-degree co-authors both for tractability reasons and to concentrate on short-distance links.

each author. For some authors—especially Buchanan and Tullock's Ph.D. students—we checked the data with their official (i.e., posted online) curricula vitae and Google Scholar. Overall, as can be seen from Figure 1, this quite dense network involves 1621 authors, including the two scholars themselves, and 1911 co-author relationships.[19] For a better appraisal of the graph, we have positioned the two founders in the middle, Buchanan being placed to the left of Tullock. The network around them is composed of three complementary subsets which gather, respectively, the 293 authors who are direct or indirect co-authors of both, denoted hereafter as "common co-authors"; the 677 authors (Tullock included) who are direct or indirect co-authors only of Buchanan, denoted hereafter "Buchanan's non-common co-authors;" and, lastly, the 651 authors (Buchanan included) who are direct or indirect co-authors only of Tullock.[20]

--- Insert Figure 1 here ---

The whole 1621-author journal publication network is thus built on the two public choice founders' direct and indirect co-authors. The natural question arises about the respective parts they play in that network, as that will convey information on the structuring of research collaborations within the public choice field (and potentially beyond). Analyzing the whole 1621-author network and its successive dyadic and triadic reductions[21] reveals that the apparent similarity of Buchanan and Tullock's characteristics (which may either come from the parallel career paths surveyed above or from a cursory observation of Figure 1) is, in fact, superficial. That first impression may be reinforced from a quick glance at the network's five centrality and connectivity measures displayed in Table 1. Looking at the degree, closeness, and betweenness measures of centrality, one might consider that Buchanan and Tullock's positions are quite similar. That is true in the full network (first two rows of Table 1), as well as the sub-networks of the common co-authors that we also explore.

--- Insert Table 1 here ---

[19] All graphs contained herein were generated with Pajek.

[20] An alternative way to apprehend the set of authors linked through direct or indirect co-authorships with Buchanan and Tullock is to analyze the two scholars' ego-networks. Buchanan and Tullock gather 969 and 943 direct and indirect co-authors involving 1122 and 1059 relationships, respectively. However, focusing on ego-networks blurs the analysis, as they, by definition, darken the overlapping part(s) of the networks. Nevertheless, for the sake of completeness, we report these two ego-networks in a graphical form, with their corresponding measures for the 40 top co-authors (that is, the equivalent of Table 3) in the online supplementary material appendix.

[21] That is, the sub-networks obtaining when considering only the authors with, respectively, at least two or three links in the 1621-author network.

However, both the Laplacian and clustering measures of centrality convey a different message: if, for the whole network, Buchanan's Laplacian measure is larger, that is no longer true for the two subnetworks, in which Tullock's measures are higher. Tullock's clustering measure also is higher (recall that a low value for clustering is a sign of a thicker network). Hence, in the whole network, Buchanan has a dense set of connections, but that is not true for the smaller subsets. As stated above, that finding reveals Tullock's influence to be in fact more "local" than Buchanan's. Moreover, the lower values for clustering signal that Buchanan is more likely to have diversified collaborations, with co-authors who are themselves loosely connected to their own co-authors, as evidenced by Figure 2 (in which the sample is restricted to the co-authors with at least three collaborations). [22]

--- Insert Figure 2 here ---

That dissimilarity is confirmed by looking at how they compare to other members of the whole network, which can be gauged by looking at the full set of measures available for each member of the network. Table 2 displays the measures for the 40 authors that got the highest measures.[23] More precisely, in Table 2, we do not report the raw measures, but a scale-transformed measure that allows one to compare any author with the maximum value obtainable in the subset, harmonized to 100. The five measures of centrality (scale-transformed[24]) are shown, and we also provide two synthetic indicators (see the last two columns): the first is an unweighted average score, while the second is the ratio of the standard error to the previous one.

--- Insert Table 2 here ---

From Table 2, it appears that both Buchanan and Tullock are featured at the top of the ranking (respectively, at the 12th and 16th positions—with corresponding scores of 52.88 and 48.87 compared to the score of the 1st ranked author, Werner Güth, 79.72). That result is not explained by the fact that they perform equally well on all the measures. In terms of degree centrality, betweenness centrality, and Laplacian centrality, their scores are relatively low. However, where

[22] So-called "triadic" reduction mentioned above.
[23] Limiting the analysis to the top 40 authors actually is the result of space limitations. The full set of results is available from the authors upon request.
[24] According to a standard feature-scaling transformation of the measures in a [0,100] range.

the two founders reach high rankings is in terms of closeness centrality and clustering connectivity. On both accounts, nevertheless, Tullock lies below Buchanan.

What this evidence reveals is that both authors are the key players in the network, as they are tied to other "central" or "connected" and, hence, influential authors on the network (as they both have low degree centrality and high closeness). Their relatively high clustering connectivity scores also reveal that they belong to (or, better say, organize around them) somewhat tightly knit groups characterized by a relatively high density of ties. Moreover, the whole picture gives a stronger role to Buchanan than to Tullock. In other words, in terms of network analysis, the role of Buchanan and Tullock appears to be central to "cliques" centered on them; these cliques being relatively large ones.[25] The exchange for that success gets exposed by low Laplacian centrality scores: even though the network is, in a way, centered on them, removing them from the network does not remove much of the "energy" it shelters. Of course, the fact that we look at the network from the present eliminates the time dimension (i.e., the way in which the network was built over time). Although it is all the more likely that the founders were, in fact, indispensable to the *creation* of the network, what is revealed here is that its organization should make the network resistant to their disappearance. In other words, Buchanan and Tullock do not rank more highly in their own co-authorship network, and removing them from the analysis does not change the network very much (Laplacian centrality). That ranking position or change can be interpreted as indicating that the field is getting more "democratic", in the sense that, if the "giants" were important, many other (less well-known) figures would try to make an intellectual community work. In other words, it seems that the giants succeeded in launching a viable academic current in economics, which proved to rely *also* on others, during and beyond the founding fathers' lifetimes.

This evidence confirms that public choice as a field of research also can be characterized as a community. As such, its evolution and functioning are well described in Boettke and Marciano (2015), and in Medema (2000, 2011), the latter of whom states: "It was a 'community' in both the broad and narrow senses: at the broader level, it led to the development of a field of analysis with its own specialized meetings and publication outlets, while in the narrower sense it was driven by the efforts of a small circle of scholars who worked together to launch this new field of inquiry."

[25] "A *clique* is a maximal subset of the vertices in an undirected network such that every member of the set is connected by an edge to every other." (Newman 2010; italics in the original).

The sense of community is also present in McKenzie and Galar's (2004) description of the atmosphere at the University of Virginia around Buchanan and Tullock. The success of this community is demonstrated by the fact that it can even now be considered as part of the mainstream (Medema, 2000, 2011).[26] Network analysis permits a better characterization of this community, revealing the role of its founding leaders in organizing the group.

4.2. Dissecting the sub-networks of "common" and "non-common" co-authors, with an overview on the role of the Public Choice *journal*

As previously detailed, Buchanan and Tullock share 293 co-authors, of whom only two—namely, Geoffrey Brennan (coded GB5)[27] and Nicolaus Tideman (NT2)—were direct (or "neighbors"), as can be seen in Figure 3 (in the figure, Brennan is right below Buchanan, while Tideman is slightly above Buchanan on the right). The question that arises pertains to the part that these common co-authors played in the structuring of the co-author network. By definition of the latter, they were the two scholars' second-closest authors whom they could be connected with through their collaboration with an intermediary—including each other—or a direct co-author. Reaching another author through common co-authors allowed for ideas, methods, tacit knowledge, in a word all the "craftsmanship" needed to produce high-quality publishable papers to flow freely. The more numerous her indirect co-authors, the more differentiated the intrinsic qualities and lessons from past collaborations can be passed on indirectly to another researcher, which herself transmits them through her collaborations.

--- Insert Figure 3 here ---

The graph representation of the 88-node sub-network (Figure 3) obtained by dyadic reduction from the "Common authors" sub-network (including Buchanan and Tullock), where each author has at least two co-authorship links in the same sub-network, supplies evidence for Buchanan and Tullock's common collaborative environment and depicts various paths connecting them to all other authors belonging to that sub-network. It clearly shows how the latter actually relies on a few authors, having either high degree (WG2, TS7) or betweenness (RT4, KG2, AH7) centrality

[26] Although this was not guaranteed from the start, and the "community" aspect even brought negative sides, at least in the beginning, as is witnessed by the refusal of the Ford Foundation to deliver financial support in the early days (see Levy and Peart 2015).

[27] Because of space constraints, the full set of codes for the co-authors analyzed in the paper is available as supplementary material (online Appendix).

and low clustering coefficients. Its five-measure average score is among the 40 highest. In passing, it must be noted that Geoffrey Brennan (GB5), one of Buchanan and Tullock's only two common direct co-authors, is linked to all of the highest-score authors of this sub-network, and that link permits him to play a key role in its connectivity and efficiency. As to the two scholars' centrality and connectivity measures for that sub-network, they do not contradict the previously underlined analysis, except with respect to Laplacian centrality, which is significantly greater for Tullock than for Buchanan here, owing to his direct co-author relationships with three authors (KG2, SB3, MI3) having high degree centrality.

Reducing the network to an "at least three co-authorship links"[28] network brings a 26-author reduction (from the 295-author "common" sub-network). As can be seen in Figure 4, in that reduced network of amplified common publication successes, few connections exist between the two founders' networks, and some players clearly are pivotal (Geoffrey Brennan, GB5, is a typical case, as well as is Werner Güth, WG2). Interestingly, the journal *Public Choice* appears as an important component of the network relations as, among the 24 authors (excluding Buchanan and Tullock), 12 have publications in the journal.

--- Insert Figure 4 here ---

The interplay of "common" and "non-common" co-authors reveals even further differences between Buchanan and Tullock. Turning to the set of "non-common" co-authors, displayed in Figures 5 (for Buchanan's network) and 6 (for Tullock's), it appears that the two founders have very differently structured (non-overlapping) networks. As Figure 5 shows, Buchanan has in fact two different sub-networks, one relatively circular, and another more linear. Tullock's network looks more "cliquish" and limited (see Figure 6, based on 22 co-authors, instead of 45 for Buchanan); with cliques that are small and clearly separated from each other. Moreover, the relative importance of *Public Choice* is different: more than 50% of the members of Buchanan's network have published in the journal, against less than one-third of Tullock's. This is even more striking given his role in the journal editorial work and may signal his high degree of integrity in that job.

--- Insert Figures 5 AND 6 here ---

[28] So-called "triadic" reduction, mentioned above.

This interpretation is in line with what is known from the respective attitudes of the two founders. Though they can probably be described as mavericks, the postures of Buchanan and Tullock as scientists were nonetheless different. Buchanan declared, in a 1982 essay, that the orthodoxies he had to confront to were "dull, dead, drab, dirty" (cited in Boettke 2014). Before that, in 1963, he considered his own views on economic practices somewhat "heretic," and insisted on economics as bearing on any type of institution in which some type of exchange could operate (and thus, becoming, at least *de facto*, a market to be examined). Also, as Boettke (2014) notes, Buchanan encouraged his students to have a "Dare to be Different" motto, while Tullock wanted students to be "irreverent." While Buchanan's reflections on "spontaneous order" guided his thought, Tullock pursued self-interest explanations, often disregarding the macro consequences of micro behavior (see Boettke 2008, and references therein). McKenzie and Galar (2004) also describe Buchanan as a leader of the rope, with Tullock encouraging him to wander more. In other words, the network analysis tends to support the impression shared by those familiar with public choice analysis, namely the idea that Buchanan provided a methodological, analytical, and ideological challenge (Buchanan, 1964), whereas Tullock invited economists to continue on with whatever they were doing persistently and consistently and to every subject (McKenzie and Tullock 1975).[29]

4.3. Influence by descendants: academic genealogy of Buchanan and Tullock's dissertation students (and co-authors)

Another way for an academic to be influential is to advise students, to co-author with them, and to encourage them advising new students, and so on. We have thus collected the names and subsequent curricula vitae of the two giants' students. That was done by accessing ETD (Virginia Tech's Electronic Theses and Dissertations) repository[30], of web searches, and the research of Medema (2000) and Tollison (1991).[31]

A clear difference is revealed on this ground between Buchanan and Tullock. As shown in Figure 7, Tullock supervised only two dissertation students, while Buchanan supervised 15 (and one of them is shared with Tullock). Moreover, Tullock's students had no further students, while the

[29] We owe this interpretation to a referee.
[30] The theses are available from the following website: https://vtechworks.lib.vt.edu/handle/10919/5534. However, not all the theses are already digitized, and the period of time covered does not yet go as far enough back in time to fully address what we require.
[31] The listing is available as a supplementary online appendix.

opposite stands for Buchanan (in particular, Robert Tollison, RT4, and Randall Holcombe, RH1, have advised numerous later generations of students).

--- Insert Figure 7 here ---

The impression of dominance by Buchanan is reinforced when one considers co-authorships with the set of individuals comprising those students. As displayed in Figure 8, Tullock's co-authoring network with "descendants" of the public choice founders is quite small, while Buchanan's is much larger and fruitful. As shown in Table 1, five of Buchanan's "children" figure in the ranking of the top 40 members of the network.

--- Insert Figure 8 here ---

If, according to Dolton (2017), a network's value is related to the social multiplier effect, then Buchanan's position in the successive networks we have described appears as more influential than Tullock's. Of course, there is more to intellectual influence than publications (Laband and Tollison 2000), and thus the effective role that any individual can play in the diffusion of a method, a technique, or simply of new results, can also vary considerably along the different dimensions a collaboration covers. It is clear that Buchanan and Tullock are key players in public choice, but, as we have seen, their centrality differs according to the measures used to uncover it. Buchanan emerges as more influential (and that was acknowledged by the Nobel committee; see Atkinson 1987), while Tullock appears as being more central, but in "cliques" of smaller sizes and, as confirmed by relations with their dissertation students, with less visible descendance.

5. Conclusion

At first sight, the academic trajectories of James M. Buchanan and Gordon Tullock are parallel and their research collaborations fruitful, starting with their co-authored book, *The Calculus of Consent* (1962), which is considered to be one of the founding contributions to the public choice field in economics. However, a more thorough look reveals, first, that they shared few common journal article and, second, that their respective co-authorship networks were structured very differently, notably with common co-authors having distinct centrality positions in each network.

Our interpretation is that the kind of complementarity evidenced by the co-authorship network analysis presented herein must be part of any retrospective explanation of the development of public choice as an established branch of the economic research. Network analysis permits us to better understand how the public choice research agenda has built up and diversified through the links between Buchanan and Tullock's most central common and non-common co-authors. Of course, one limitation of the analysis is that it does not tell us how the links between the different co-authors emerged over time, and how the relations evolved (becoming stronger or looser). Unfortunately, there is yet no established way of uncovering the time dimensions of established networks, although computer scientists are developing tools that should soon facilitate detecting both the temporal and structural nature of scholarly interactions (see Gaumont et al. 2016; Latapy et al. 2017).

Beside this perspective, which will deserve close attention in future research, we must restate that it goes beyond the scope of this paper to ask whether James Buchanan and Gordon Tullock's parallel careers resulted from several conscious choices, a purposeful strategy for disseminating ideas through distinct networks, or if their partnership simply was an accidental feature of academic life, with different branches growing out of the same tree. The answer may lie in the complete papers of James M. Buchanan and Gordon Tullock (the Buchanan House of George Mason University, which hosts the archives of the Center for Study of Public Choice, archives Buchanan's papers, but the Hoover Institution houses Tullock's). Time (and the biographers) may thus give us deeper hindsights into the foundations and evolutions of their scholarly enterprises.

Acknowledgements

Without implication, we thank the editors and the reviewers of the journal for stimulating suggestions, as well as Stefan Balev, Bruno Beaufils, Hamza Bennani, Peter Boettke, Hakim Hammadou, Daniel Houser, Fabio Padovano and Yann Secq for useful discussions and remarks, as well as participants in the workshop on "Interdisciplinary approaches on co-authorship and scientific networks" (Le Havre, May 2016). Steven Medema deserves special thanks for his precious help in effectively getting Robert Tollison's 1991 paper (containing the list of Virginia's Political Economy Graduate students).

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Table 1

Individual centrality and connectivity measures (whole network and two subsets)

Measure	Degree	Closeness	Betweenness	Laplacian	Clustering (CC1)
(a) Whole network (1621 authors)					
Buchanan	21	0.309	0.141	808	0.033
Tullock	19	0.305	0.109	754	0.105
(b) Sub-network: reduction to authors with at least two direct co-authors (281 authors)					
Buchanan	17	0.376	0.158	576	0.045
Tullock	17	0.37	0.112	610	0.099
(c) Sub-network: reduction to authors with at least two direct co-authors in the "common" subset (88 authors)					
Buchanan	12	0.421	0.188	296	0.106
Tullock	16	0.445	0.172	456	0.150

Source: authors.

Table 2.
Individual centrality and connectivity
40 highest ranked authors in the whole network (1621 authors)

Author	Code	Degree centrality	Closeness centrality	Betweenness centrality	Laplacian centrality	Clustering connectivity	*Average unweighted score*	*Standard error / average*
Werner Güth	WG2	100.00	78.83	20.76	100.00	98.98	*79.72*	*0.43*
Friedrich Schneider	FS5	96.25	80.96	25.32	90.96	99.97	*78.69*	*0.39*
Robert Tollison	RT4	47.50	99.58	100.00	40.36	94.20	*76.33*	*0.39*
Kevin Grier	KG2	35.00	100.00	73.65	22.56	95.32	*65.31*	*0.54*
Todd Sandler	TS7	71.25	75.17	20.27	52.75	100.00	*63.89*	*0.46*
Arnold Harberger	AH7	32.50	90.81	55.62	20.50	94.02	*58.69*	*0.57*
William Shughart	WS4	53.75	80.88	11.76	36.29	97.36	*56.01*	*0.61*
Richard Just	RJ1	56.25	74.83	14.22	32.79	100.00	*55.62*	*0.61*
Harmut Kliemt	HK1	55.00	78.93	11.15	35.41	97.58	*55.61*	*0.62*
Maria Levati	ML1	53.75	77.69	9.89	33.66	97.78	*54.55*	*0.64*
Geoffrey Brennan	GB5	20.00	96.03	51.00	14.77	90.44	*54.45*	*0.70*
James Buchanan	*JBU*	*25.00*	*95.40*	*35.97*	*11.35*	*96.67*	*52.88*	*0.76*
David Laband	DL1	46.25	79.63	12.48	26.83	99.15	*52.87*	*0.68*
Eytan Sheshinski	ES6	46.25	80.42	12.17	24.63	98.29	*52.35*	*0.70*
John Jackson	JJ1	42.50	77.12	7.68	22.68	97.98	*49.59*	*0.76*
Gordon Tullock	*GTU*	*22.50*	*94.06*	*27.75*	*10.59*	*89.47*	*48.87*	*0.81*
James Lothian	JL3	37.50	73.82	10.89	16.55	99.78	*47.71*	*0.80*
Francis Teal	FT2	37.50	74.44	8.79	15.36	100.00	*47.22*	*0.83*
Laura Razzolini	LR1	36.25	76.57	7.73	16.41	98.85	*47.16*	*0.83*
Dennis Mueller	DM7	32.50	81.15	8.68	13.47	99.43	*47.04*	*0.87*
Michael Darby	MD4	37.50	72.62	8.65	17.71	98.71	*47.04*	*0.81*
Boyan Jovanovic	BJ1	36.25	70.77	10.68	15.42	99.54	*46.53*	*0.82*
Keith Hartley	KH2	32.50	74.52	10.94	13.50	99.72	*46.23*	*0.85*
Michael Intriligator	MI3	21.25	91.30	22.47	11.72	84.31	*46.21*	*0.83*
Randall Holcombe	RH1	33.75	76.10	7.06	14.40	98.94	*46.05*	*0.87*
Serguey Braguinsky	SB3	21.25	79.89	28.50	10.34	90.20	*46.03*	*0.79*
Yew Kwang Ng	YN2	32.50	75.94	8.33	12.48	100.00	*45.85*	*0.88*
Mark Spiegel	MS8	38.75	64.44	8.86	16.72	99.60	*45.67*	*0.81*
Thomas Willett	TW1	26.25	80.24	8.95	11.69	98.27	*45.08*	*0.92*
Arleen Leibowitz	AL5	30.00	76.04	7.39	10.93	100.00	*44.87*	*0.92*
Richard Wagner	RW2	17.50	83.15	15.47	8.30	98.10	*44.50*	*0.96*
Joseph François	JF11	28.75	76.22	6.85	10.36	99.64	*44.36*	*0.93*
Steven Klepper	SK9	33.75	65.63	7.73	12.99	99.74	*43.97*	*0.88*
Mwangi Kimenyi	MK6	25.00	79.32	6.17	9.86	98.57	*43.78*	*0.97*
Sebastian Edwards	SE1	30.00	70.82	6.85	11.47	99.33	*43.69*	*0.92*
Roger Congleton	RC12	17.50	82.90	12.91	7.65	97.14	*43.62*	*0.98*
Michael Munger	MM14	23.75	80.04	5.98	8.75	98.42	*43.39*	*0.99*
David Levy	DL4	26.25	76.55	6.92	10.42	95.67	*43.16*	*0.94*
Yeon-Koo Che	YC2	28.75	69.89	6.82	9.43	100.00	*42.98*	*0.95*
Ryan Oprea	RO3	28.75	68.16	6.89	9.55	100.00	*42.67*	*0.95*

(*) Let *f* be the standard feature-scaling transformation of author *i*'s score x_i in measure M, such that**:**

$f(x, M) = 100 \times (x_M^i - x_M^-)/(x_M^+ - x_M^-)$, with $x_M^- = \min(x_M^1, \cdots, x_M^i, \cdots, x_M^{1621})$ and $x_M^+ = \max(x_M^1, \cdots, x_M^i, \cdots, x_M^{1621})$

Note: Code refers to the coding of the whole set of authors used in the Appendix.

Source: authors.

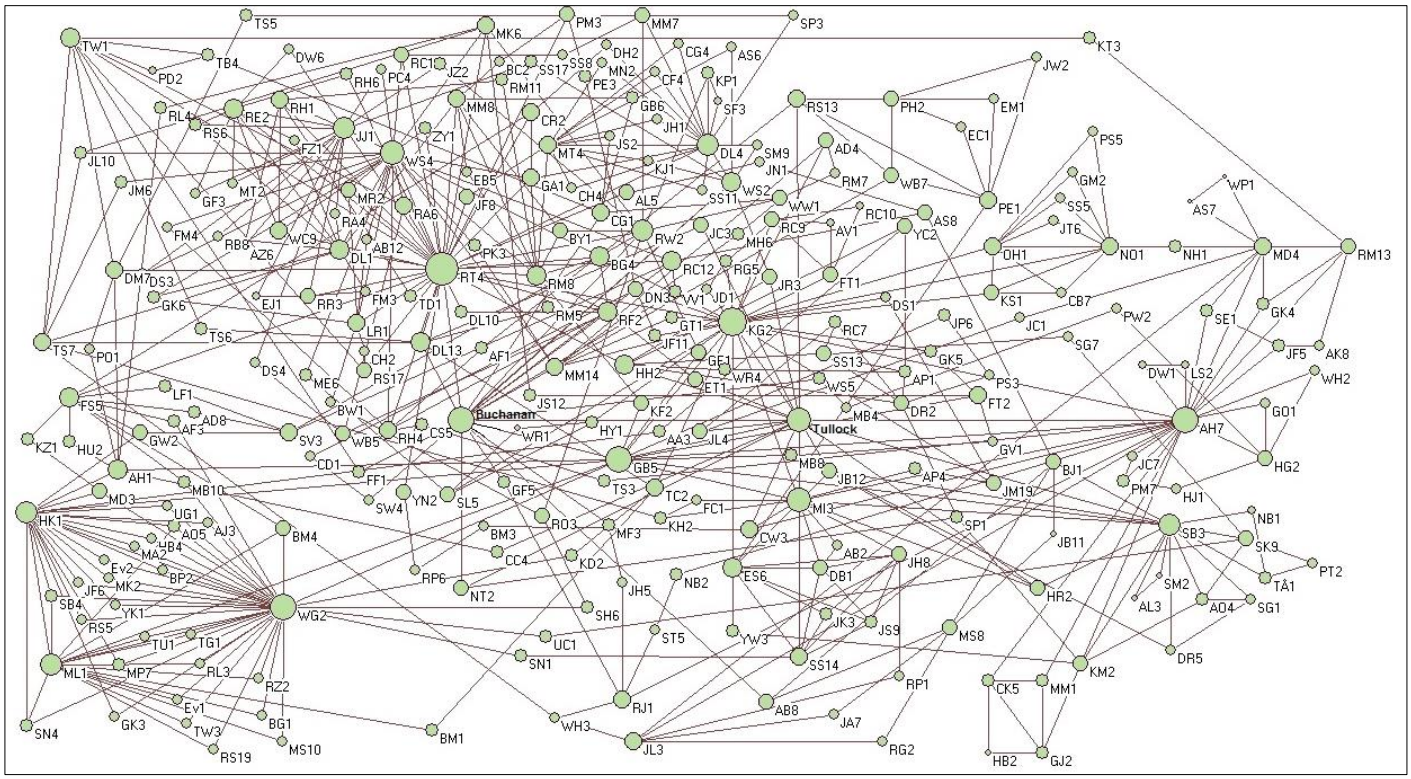

Figure 1. Buchanan and Tullock co-authorship network (at least two collaborators)

Note: 281-author reduction of the whole 1621-author network, keeping only co-authors having at least two co-authorship links. Size of vertex is proportional to its unweighted average score in centrality (degree, betweenness and Laplacian) and connectivity (clustering).

Source: authors.

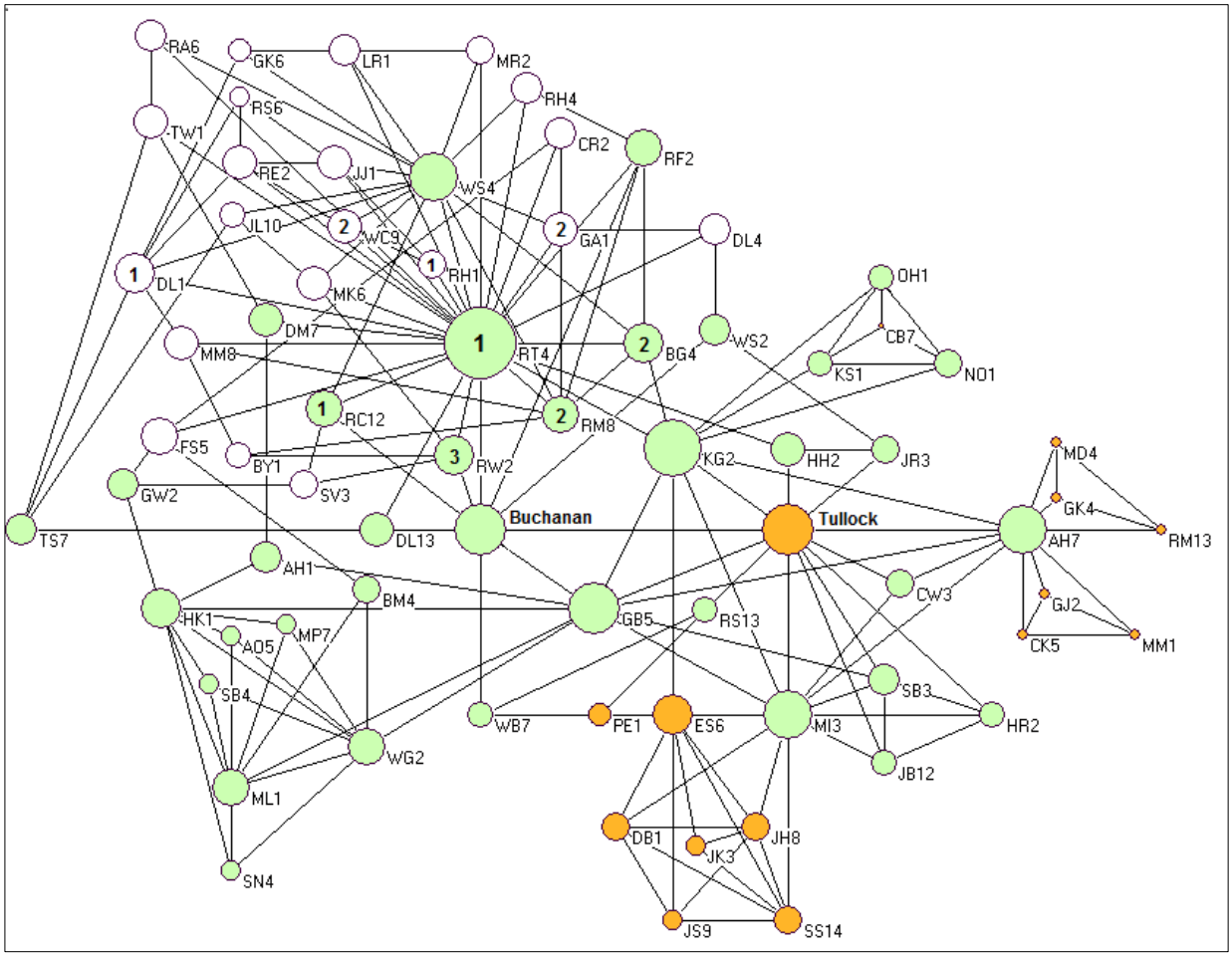

Figure 2. Buchanan and Tullock co-authorship sub-network (at least three collaborators)

Note: 73-author sub-network of the 1621-author whole network, each author having at least three direct co-authors. Size of vertex (author) is proportional to its unweighted average score in degree, betweenness, Laplacian centrality, and clustering. Vertex color shade indicates which sub-network it belongs to Buchanan's non-common co-authors (blank), Buchanan and Tullock's common co-authors (light), and Tullock's non-common co-authors (dark). Number on vertex refers to the corresponding author's PhD adviser: 1 (Buchanan), 2 (Tollison), and 3 Buchanan & Tullock).

Source: authors.

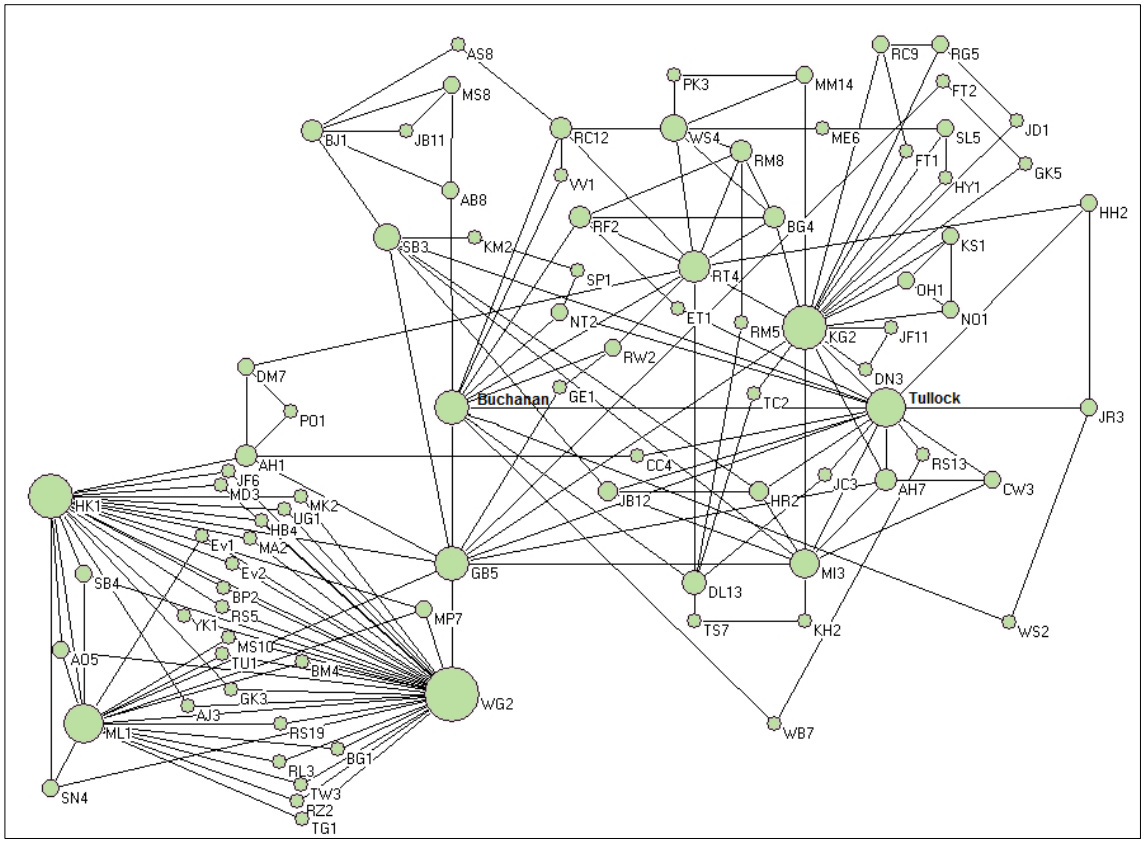

Figure 3. Buchanan and Tullock *common* co-authorship sub-network (88-author reduction)

Note: 88-author reduction of 295-author "common" sub-network (including Buchanan and Tullock), where each author has at least two co-authorship links in this same sub-network. Size of vertex (author) is proportional to its unweighted average centrality and connectivity score in the 1621-node network.
Remark: 22 of these 88 co-authors are among the 40 highest ranked authors *w.r.t.* their average centrality and connectivity scores (see Table 3).
Source: authors.

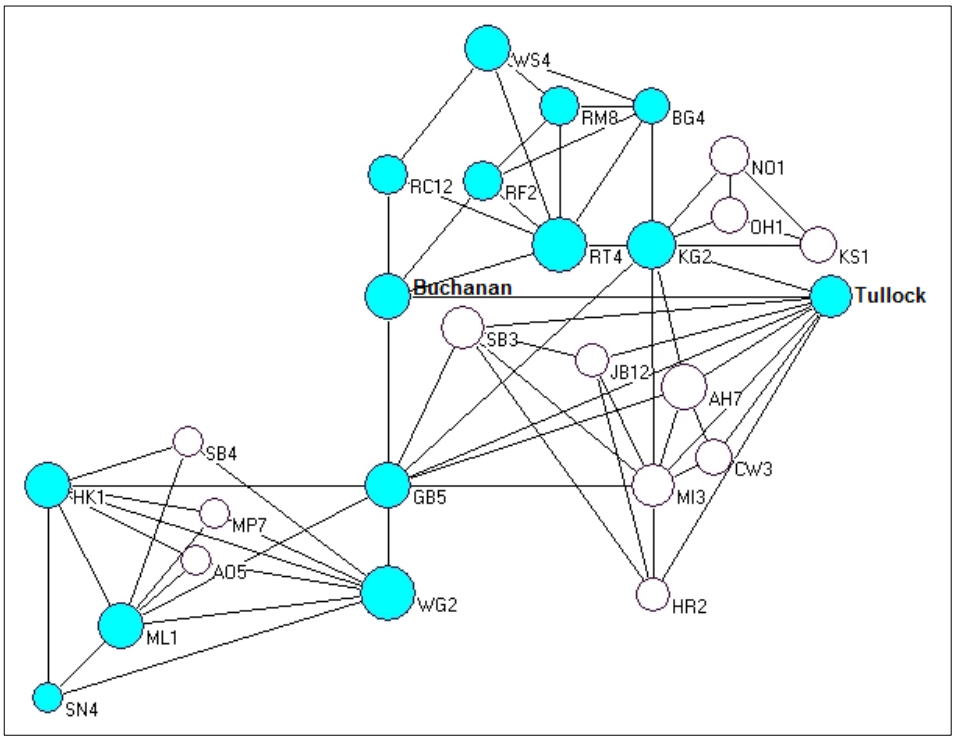

Figure 4. Buchanan and Tullock *common* co-authorship sub-network (26-author reduction)

Note: 26-author reduction of 295-author "common" sub-network, where each author has at least three co-authorship links. Color-filled vertices are co-authors who published at least one article in *Public Choice* journal. Size of vertex (author) is proportional to its unweighted average centrality and connectivity score in the 1621-node network.
Remark**:** 13 of these 26 authors are among the 40 highest ranked authors in full network *w.r.t.* their average centrality and connectivity scores (see Table 3).
Source: authors.

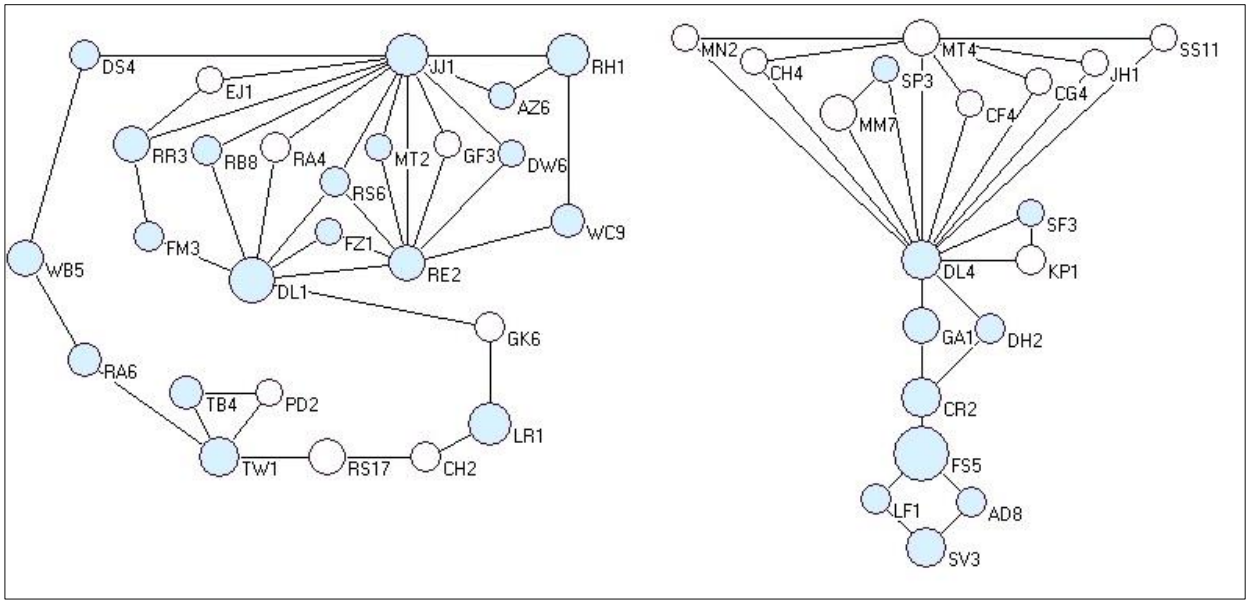

Figure 5. Buchanan *non-common* co-authorship sub-network

Note: 45-author reduction of Buchanan's "non common" co-authors network, with each author having at least two direct co-authors. Size of vertex (author) is proportional to its unweighted average centrality and connectivity score in the 1621-node whole network. Filled vertices are co-authors with at least one article published in *Public Choice* journal.
Source: authors.

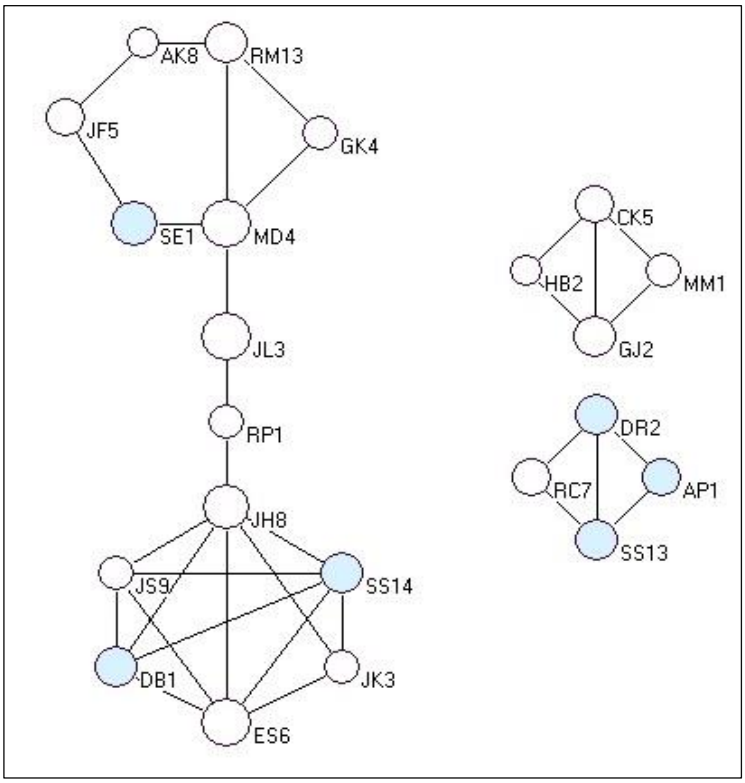

Figure 6. Tullock *non-common* co-authorship sub-network

Note: 22-node dyadic reduction of Tullock's "non-common" co-author network. Size of vertex (author) is proportional to its unweighted average centrality and connectivity score in the 1621-node network. Filled vertices are co-authors with at least one article published in *Public Choice* journal.
Source: authors.

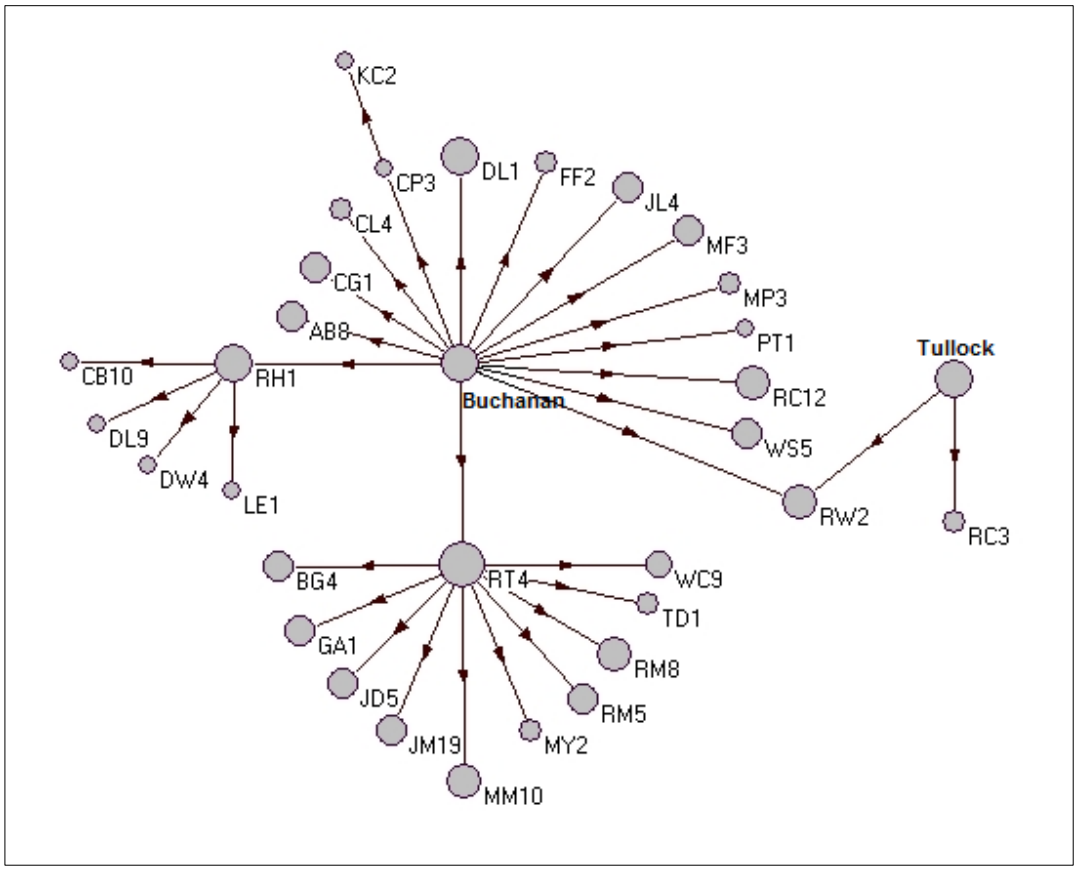

Figure 7. Buchanan and Tullock's Ph.D. "children and grandchildren"

Note: X→Y reads: "X was Y's PhD dissertation adviser." Size of vertex is proportional to its unweighted average score in the 1621-node whole network.
Source: authors.

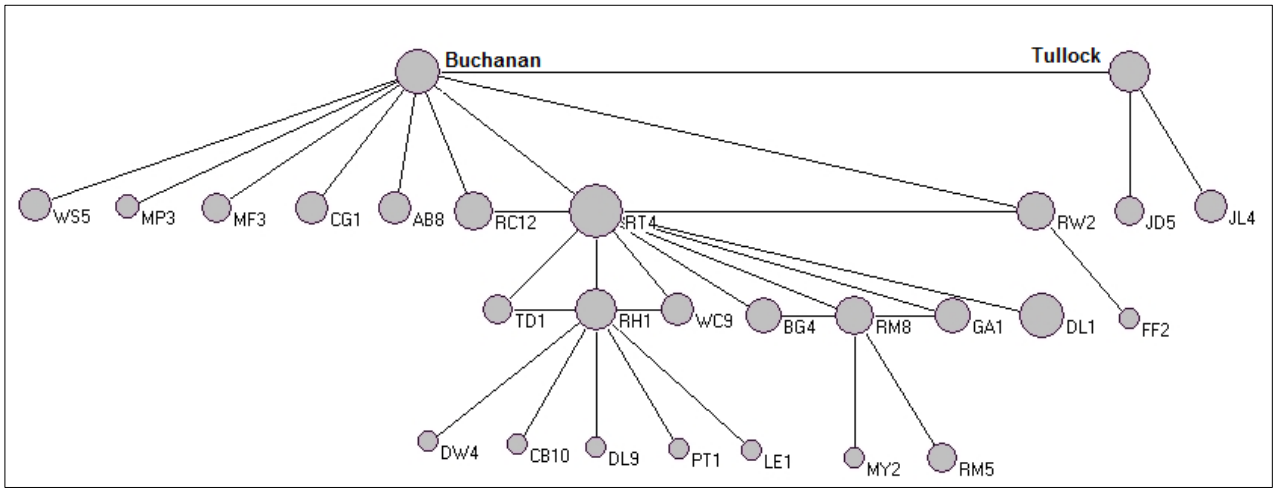

Figure 8. Buchanan and Tullock's co-authorships with their Ph.D. "children and grandchildren"

Note: Co-authorship links in the whole 1621-node network between PhD dissertation advisers (Buchanan, Tullock, Holcombe, and Tollison) and their ex-PhD students, and between former Ph.D. students.

Source: authors.