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Appendix 1

1.1 Sample

Social characteristics (for SET in the first part of Table 1) exist for almost the entire dataset (including SSH), with only seven individuals missing information on birth year, gender, skin color, or citizenship. Birth year ranges between 1926 and 1985 with an interquartile range of 1953–1969 and a median of 1961. About one-third of the scientists are female, two-thirds are male. The majority, two-thirds (3037), of scientists is white, according to the apartheid racial categorization.²⁵ A majority, 80%, has South African citizenship (including permanent residents), only 5% are from the rest of Africa. Most scientists with non-South African citizenship, 10% of the sample, have European citizenship, mostly from the UK followed by Germany.

Information on scientific careers is less complete, with about 11 missing (some) information (see the second part of Table 1). The scientific domain shows twice as many scientists in the sciences (SET) as in social sciences and humanities (SSH). However, for around 10% of the population, we are missing data on academic degrees (bachelor or master as first academic degree and PhD) and employments.²⁶

Until 2002, the NRF rated only researchers within the domain of science, engineering, and technologies (SET) where ratings diffused relatively fast and seem to have saturated by 1995

²⁵ Racism, in particular during the Apartheid regime, produced strong socio-economic differences by color of skin for which we control with this variable.

²⁶ For individuals where first South African employment is known, we have very complete information on the overall employment trajectory.

(suggested e.g. by NRF, 2005, p.18, Fig.: total number of rated researchers in SET: 1985–2003). In 2002, the rating system was expanded to include social sciences and humanities (SSH). In our dataset, in that first year around 207 SSH researchers obtained their first NRF rating compared to 32 SET researchers. In the subsequent three years, until 2005, further catching-up happens. The ratio of SSH to SET in terms of first ratings then normalizes to around 1:2. On the other hand, the panel that we construct from the rating data displays each year (from 1996 to 2014) that same ratio of 1:2 in terms of active researchers. Thus, the relatively late inclusion of SSH does not lead to a shifting composition of the scientific domain in our panel.

There is no strong pattern of missing information over disciplines, except for arts with 18% missing. Also, foreign and local graduates have similarly few missing observations. Missing information is particularly high for older scientists, born in the 1940s and 1950s, and those scientists with a last rating in the year 2002, 2003, or 2004. It seems possible that in particular older scientists with some reputation managed to sidestep a complete digital filing in the earlier years of the NRF data platform, perhaps with a reference to earlier dossiers in paper format.

All individuals in the sample have (by sample construction) at least one valid rating during the period 1990–2015, with seven being the maximum number of ratings observed for one individual.

For scientific output (peer-reviewed journal and conference papers), the extent of missing information is not immediately clear because no (or low) publication counts are in principle possible. The scientific discipline with the largest number of researchers showing no journal articles is arts (10%) where other outputs may be more relevant. In this discipline, collaboration is probably in general not well proxied by paper co-authors. In all other disciplines, only 1% or less did not file any journal articles. In the natural sciences, nearly all scientists filed peer-reviewed journal articles. In these disciplines, zero publication entries may indeed signal missing data.

1.1.1 Network sample

Co-author networks are used not only to count foreign ties of our focal scientists but also to measure the network context in which foreign ties are acquired. Therefore, we aim at an exhaustive description of the network, covering South African scientific collaboration as much as possible, by including in particular papers of rated scientists that are not part of the main sample.

The data creation process itself has implications for network construction. Scientists entered their (past) publications during a period from 2002 and 2014 for various programs run by the NRF. They enter their scientific output up to the time of filing for a rating (or a project) application. Thus, a unique article enters the data twice in case two different scientists file the same, co-authored paper.²⁷ The potential duplication of co-author links prompts us to work with unweighted, binary networks. On the other hand, papers are missed if the paper is published after the last filing of a scientist. This leads us to drop focal scientists from the panel at the year before their last filing because foreign ties are observed only partly or not at all thereafter. A second effect is a potential measurement error on the collaboration network among South African scientists.

Publication data fields include among other things publication year, publication type, (co-)authors, title, and journal. After some initial cleaning,²⁸ we obtain 308,412 publication entries with publication dates between 1990 and 2014; 235,712 peer-reviewed journal articles and 72,700 peer-reviewed conference proceedings. The main analysis is based on peer-reviewed journal articles. This avoids duplication of collaboration ties when a conference paper is subsequently published in a journal.

Disambiguation of co-authors is based on information within the NRF dataset. We proceed sequentially. In a first step, the scientist filing a paper is identified by name (surname and initials). In a second step, co-author names are matched to a list of 5,255 scientists rated by NRF between 1984 and 2017. In a third step, remaining names are matched to non-rated NRF users. These

²⁷ Because there is no unique paper identifier available, we do not know the exact number of unique papers. Titles, journal names, etc. in the data are strings entered by the applicants in various ways and hence cannot serve as identifiers without further cleaning.

²⁸ The initial cleaning entails essentially two parts. First, joining two NRF data snapshots with different data structures but partly overlapping time periods. Second, identification of individual author names (surname and initials) within each paper's author list as these have been entered by the applicant in a free format string.

include for example South African PhDs but also local and foreign scientists. The sequential matching is based on the following assumption: if there exist two individuals with the same name as one of the authors, the author is more likely (i) the filing scientist rather than the other individual, else (ii) the NRF rated scientists rather than the other individual, else (iii) some scientist dealing with the NRF rather than an individual who does not. In case identification within each of these three steps is ambiguous, we keep the author as unidentified throughout. Finally, for all author names not found in the NRF dataset, a one-to-one correspondence between author name and individual is assumed. True, this final decision may conflate two individuals with the same name. We checked on the whole sample that this issue is not too severe. In addition, we construct networks only within disciplines such that different individuals from different disciplines are not conflated.²⁹

Our disambiguation procedure leads to the following numbers: the 235,712 peer-reviewed journal articles give rise to 866,024 author name–paper relations (‘author-papers’). Around 25% of author papers are associated with the postulating rated scientist, 15% can be attributed to non-postulating rated scientists, 17% are found among non-rated scientists registered in the NRF system, and for the remaining 41% we take the name as the individual. Around 4% of author papers are ambiguous in that there are multiple individuals in the NRF dataset with the same name and initials. For the main analysis, we remove these ambiguous cases. Sixty-one focal scientists are not associated with any peer-reviewed journal article.³⁰ This disambiguation of names yields 163,591 authors (individuals).

1.2 Basic descriptives

Basic descriptives include statistics on Social Science and Humanities (SSH), but the focus is clearly on Science, Engineering, and Technologies (SET), and ultimately our analysis will be restricted to those domains.

1.2.1 Scientific fields

Table A1 provides the number of panel observations (year-scientists) and individuals (scientists) by scientific discipline along the formation of foreign and SA co-author ties. Within the ‘Science and Technology’ domain, physicists have on average most collaborations per year (9.25 collaborations per scientist-year) and the highest share of foreign ties (55% of all ties are foreign). For computer scientists, we measure relatively few collaboration ties and a relatively low share of foreign ties. This may be due to the prevalence of conference proceedings over journal articles in the field. Most natural sciences have on average around 30% foreign ties (per scientist-year).

In Social Science and Humanities, Arts is the most foreign-oriented field conditional on its relatively small number of overall co-author ties. Economics and social sciences form most co-author ties per scientist-year with the highest foreign orientation among SSH but still low compared to the foreign tie formation observed in SET fields.

1.2.2 Higher education and the development of foreign social capital

Higher education may be obtained in South Africa, abroad, or both. We classify origin of higher education by the first higher education degree³¹ and the PhD. Higher education is denoted ‘‘South African’’ if both the first higher degree and PhD have been obtained in South Africa. It is denoted ‘‘foreign’’ when both degrees have been obtained abroad. The ‘‘second-diagonal’’ cases are ‘‘South African-foreign,’’ and ‘‘foreign-South African.’’

The origin of higher education is related to the age of the PhD graduate. In general, foreign-trained PhDs earn their doctorate earlier than locally trained PhDs. Focal scientists with a fully foreign higher education earn their doctorates at a median age of 31, which corresponds to the age of the median US PhD (<https://nces.nsf.gov/pubs/nsf20301/data-tables>). Focal scientists fully

²⁹ This implies that, by construction, we do not observe diffusion of co-author ties across disciplines.

³⁰ 36 did not postulate an article (mostly in arts). 25 postulated an article that has been removed during the initial cleaning process (e.g., due to missing publication date).

³¹ In most cases, the first higher education degree is a bachelor degree or comparable variant; if that is not available, we use the master degree as a proxy.

Table A1. Tie formation by scientific fields

	Observations	Individuals	SA ties	Foreign ties	Total ties	Ties obs.	Foreign ties
<i>Science, Engineering and Technologies (SET)</i>							
Agricultural	2562	251	10012	3858	13870	5.41	0.28
Biological	4552	417	22092	10831	32923	7.23	0.33
Chemical	1692	162	8310	2360	10670	6.31	0.22
Earth and marine	2402	231	7799	4159	11958	4.98	0.35
Health	4909	488	31119	14373	45492	9.27	0.32
ICT	1407	150	1666	432	2098	1.49	0.21
Mathematical	1899	169	2616	1404	4020	2.12	0.35
Physical	2237	222	9246	11451	20697	9.25	0.55
Technologies	3353	349	9354	3068	12422	3.71	0.25
<i>Social Sciences and Humanities (SSH)</i>							
Arts	933	89	195	132	327	0.35	0.40
Economic	1631	159	2213	670	2883	1.77	0.23
Humanities	4911	418	2755	441	3196	0.65	0.14
Law	1662	150	836	128	964	0.58	0.13
Social	3529	326	4348	1197	5545	1.57	0.22

Fisher's exact test rejects the Null hypothesis that foreign and SA tie formation is independent of scientific fields at a significance level of below 0.00049 (over all scientific fields, within SET, and within SSH).

formed in South Africa take around 3 years longer (median 34). Scientists with “South African–foreign” higher education graduate with a PhD slightly earlier (median 33), while ‘foreign–South African’ take three more years (median 37). The interquartile range for SA formed scientists is 30–38 years and shifted down by two to four years for fully trained foreign. We observe that same tendency across scientific fields with some smaller variation. In general, age at PhD is higher for SSH than for SET.

Time to first SA employment after PhD, and hence experience gathered elsewhere, also varies by origin of higher education. 90% of focal scientists with a PhD earned in South Africa start an SA employment within 5 years from the doctorate. 80% with ‘South African–foreign’ education ‘return home’ for SA employment within 5 years. On the other hand, only 50% of foreign-educated focal scientists entered the SA higher education system within 5 years after their PhD. Most fully foreign-trained scientists enter between 2 and 10 years after PhD (interquartile range), with 7 years of experience on average. On the other hand, 75% of SA scientists start first employment after PhD within 2 years from graduation (4 years for ‘South African–foreign’). This pattern, again, holds across scientific disciplines.

Table A2 looks at how foreign ties are acquired, from time of entry into the SA system (i.e., $t \geq 0$), by origin of education, for the SET and SSH subsamples, respectively. First consider the absolute numbers, which are average number of ties (of a certain kind) over all scientist-year observations from time of entry into the SA system (i.e., $t \geq 0$). For foreign-trained scientists, we see more foreign ties than for the other groups. That holds for the total number of foreign ties (last column), the different ways of acquisitions (the other columns), and for both subsamples (SET and SSH).

Furthermore, patterns of foreign tie formation differ by origin of higher education. Consider the proportions of tie formation motifs given in the brackets (Table A2). Foreign-trained scientists seem more “independent” in foreign tie formation as they establish relatively often unique ties to new foreign co-authors (and less joint acquisitions) and are more likely to repeat existing ties (and use to a lesser extent referrals within SA).

1.3. Extensions

This section provides the statistics underlying the figures in Section 4.2

Table A2. Motifs of tie formation by higher education for subsamples SET and SSH, average (proportion)

	new unique	new joint	repeated	referral	others	foreign ties
<i>Science, Engineering and Technologies (SET)</i>						
SA	0.26 (0.183)	0.684 (0.480)	0.378 (0.265)	0.063 (0.044)	0.039 (0.028)	1.425 (1)
For	0.622 (0.231)	0.908 (0.337)	0.966 (0.359)	0.092 (0.034)	0.102 (0.038)	2.69 (1)
SA-For	0.312 (0.205)	0.639 (0.419)	0.47 (0.308)	0.066 (0.043)	0.037 (0.024)	1.525 (1)
For-SA	0.241 (0.161)	0.765 (0.51)	0.371 (0.247)	0.077 (0.052)	0.045 (0.03)	1.5 (1)
<i>Social Sciences and Humanities (SSH)</i>						
SA	0.038 (0.209)	0.094 (0.515)	0.047 (0.257)	0.002 (0.012)	0.001 (0.007)	0.183 (1)
For	0.081 (0.310)	0.114 (0.438)	0.065 (0.249)	0.001 (0.003)	0 (0)	0.261 (1)
SA-For	0.045 (0.252)	0.087 (0.486)	0.042 (0.236)	0.002 (0.013)	0.002 (0.013)	0.179 (1)
For-SA	0.096 (0.303)	0.163 (0.514)	0.047 (0.149)	0.009 (0.029)	0.002 (0.005)	0.317 (1)

Table A3. Higher education origin (ind., obs.), outcome (freq.), and model statistics (m1, m2, sargan, moran's I diff., moran's I level) of estimations shown in Figure 3.

m1	Model 1				Model 2					
	m2	sargan	moran diff	moran level	m1	m2	sargan	moran diff	moran level	
<0.001	0.198	0.286	<0.001	<0.001	<0.001	0.095	0.796	0.003	0.005	
<i>South African HE (961, 10180), for. ties (13474)</i>										
<0.001	0.043	0.846	0.793	0.511	<0.001	0.044	0.84	0.77	0.563	
<i>South African HE (961, 10180), unique acq. (2401)</i>										
<0.001	0.117	0.164	<0.001	<0.001	<0.001	0.369	0.76	<0.001	<0.001	
<i>South African HE (961, 10180), joint acq. (6542)</i>										
<0.001	0.688	0.085	<0.001	<0.001	<0.001	0.744	0.077	<0.001	<0.001	
<i>South African HE (961, 10180), repeated (3524)</i>										
<0.001	0.052	0.167	<0.001	<0.001	<0.001	0.052	0.132	<0.001	<0.001	
<i>South African HE (961, 10180), co-auth. ref. (524)</i>										
<0.001	0.04	0.31	<0.001	<0.001	<0.001	0.04	0.184	<0.001	<0.001	
<i>South African HE (961, 10180), faculty ref. (628)</i>										
<0.001	0.262	0.316	<0.001	<0.001	<0.001	0.263	0.172	<0.001	<0.001	
<i>South African HE (961, 10180), other (379)</i>										
<0.001	0.545	0.485	0.217	0.011	<0.001	0.925	0.032	0.802	0.057	
<i>foreign HE (333, 3345), for. ties (7953)</i>										
<0.001	0.879	0.78	0.985	0.981	<0.001	0.975	0.776	0.96	0.899	
<i>foreign HE (333, 3345), unique acq. (1795)</i>										
<0.001	0.3	0.907	<0.001	<0.001	<0.001	0.225	0.952	<0.001	<0.001	
<i>foreign HE (333, 3345), joint acq. (2733)</i>										
<0.001	0.677	0.193	0.953	0.029	<0.001	0.485	0.114	0.86	0.226	
<i>foreign HE (333, 3345), repeated (2814)</i>										
<0.001	0.129	0.728	<0.001	<0.001	<0.001	0.148	0.896	<0.001	<0.001	
<i>foreign HE (333, 3345), co-auth. ref. (263)</i>										
<0.001	0.191	0.831	<0.001	<0.001	<0.001	0.173	0.856	<0.001	<0.001	
<i>foreign HE (333, 3345), faculty ref. (301)</i>										
<0.001	0.262	0.816	0.704	0.975	<0.001	0.275	0.793	0.702	0.98	
<i>foreign HE (333, 3345), other (310)</i>										

Table A4. Scientific field (ind., obs.) and outcome (freq.) and model statistics (m1, m2, sargan, moran's I diff., moran's I level) of estimations shown in Figure 4

m1	Model 1				Model 2					
	m2	sargan	moran diff	moran level	m1	m2	sargan	moran diff	moran level	
< 0.001	0.402	0.664	<0.001	<0.001	<0.001	0.875	0.525	0.3	0.106	
<i>Biological sciences (288, 2890), for. ties (5767)</i>										

(continued)

Table A4. (Continued)

Model 1					Model 2				
m1	m2	sargan	moran diff	moran level	m1	m2	sargan	moran diff	moran level
			<i>Biological sciences (288, 2890), unique acq. (1334)</i>						
<0.001	0.906	0.733	0.999	0.834	<0.001	0.922	0.613	1	0.832
			<i>Biological sciences (288, 2890), joint acq. (2656)</i>						
<0.001	0.943	0.789	<0.001	<0.001	<0.001	0.654	0.86	0.002	0.002
			<i>Biological sciences (288, 2890), repeated (1360)</i>						
<0.001	0.599	0.348	0.002	<0.001	<0.001	0.195	0.39	0.05	0.004
			<i>Biological sciences (288, 2890), co-auth. ref. (184)</i>						
<0.001	0.074	0.543	<0.001	<0.001	<0.001	0.032	0.483	<0.001	<0.001
			<i>Biological sciences (288, 2890), faculty ref. (231)</i>						
<0.001	0.321	0.263	<0.001	<0.001	<0.001	0.081	0.471	<0.001	<0.001
			<i>Biological sciences (288, 2890), other (186)</i>						
<0.001	0.671	0.291	0.069	0.032	<0.001	0.629	0.303	0.082	0.071
			<i>Earth and marine sciences (143, 1448), for. ties (2184)</i>						
<0.001	0.75	0.609	0.025	0.001	<0.001	0.8	0.853	0.978	0.864
			<i>Earth and marine sciences (143, 1448), unique acq. (510)</i>						
<0.001	0.72	0.625	1	0.753	<0.001	0.759	0.598	0.995	0.66
			<i>Earth and marine sciences (143, 1448), joint acq. (947)</i>						
<0.001	0.413	0.427	<0.001	<0.001	<0.001	0.771	0.273	0.016	0.015
			<i>Earth and marine sciences (143, 1448), repeated (590)</i>						
<0.001	0.575	0.108	0.157	0.018	<0.001	0.657	0.161	0.226	0.057
			<i>Earth and marine sciences (143, 1448), co-auth. ref. (67)</i>						
<0.001	0.513	0.791	1	0.315	<0.001	0.48	0.674	1	0.463
			<i>Earth and marine sciences (143, 1448), faculty ref. (80)</i>						
<0.001	0.437	0.762	0.999	0.28	<0.001	0.382	0.707	1	0.46
			<i>Earth and marine sciences (143, 1448), other (57)</i>						
0.004	0.778	0.658	0.011	0.001	0.003	0.758	0.907	0.003	0.001
			<i>Health Sciences (296, 3012), for. ties (6266)</i>						
<0.001	0.123	0.029	<0.001	<0.001	<0.001	0.265	0.263	0.089	0.273
			<i>Health Sciences (296, 3012), unique acq. (928)</i>						
<0.001	0.121	0.686	0.299	0.048	<0.001	0.124	0.634	0.347	0.036
			<i>Health Sciences (296, 3012), joint acq. (3250)</i>						
<0.001	0.189	0.24	<0.001	<0.001	<0.001	0.81	0.648	<0.001	<0.001
			<i>Health Sciences (296, 3012), repeated (1589)</i>						
<0.001	0.517	0.007	<0.001	<0.001	<0.001	0.547	0.01	0.002	<0.001
			<i>Health Sciences (296, 3012), co-auth. ref. (232)</i>						
<0.001	0.1	0.289	0.002	<0.001	<0.001	0.099	0.226	0.003	<0.001
			<i>Health Sciences (296, 3012), faculty ref. (286)</i>						
<0.001	0.084	0.276	0.003	<0.001	<0.001	0.083	0.181	0.004	<0.001
			<i>Health Sciences (296, 3012), other (213)</i>						
<0.001	0.679	0.59	0.015	<0.001	<0.001	0.574	0.482	0.02	0.002
			<i>Physical sciences (107, 1152), for. ties (4444)</i>						
<0.001	0.616	0.776	0.057	0.004	<0.001	0.948	0.619	0.589	0.015
			<i>Physical sciences (107, 1152), unique acq. (650)</i>						
<0.001	0.326	0.619	0.951	0.152	<0.001	0.329	0.586	0.943	0.109
			<i>Physical sciences (107, 1152), joint acq. (1482)</i>						
<0.001	0.878	0.966	<0.001	0.001	<0.001	0.948	0.663	0.004	0.001
			<i>Physical sciences (107, 1152), repeated (1776)</i>						
<0.001	0.726	0.461	0.159	0.002	<0.001	0.755	0.28	0.281	0.072
			<i>Physical sciences (107, 1152), co-auth. ref. (276)</i>						
0.003	0.635	0.331	<0.001	<0.001	0.004	0.654	0.422	<0.001	<0.001
			<i>Physical sciences (107, 1152), faculty ref. (299)</i>						
0.001	0.603	0.499	<0.001	<0.001	0.001	0.59	0.657	0.001	0.001

(continued)

Table A4. (Continued)

Model 1					Model 2				
m1	m2	sargan	moran diff	moran level	m1	m2	sargan	moran diff	moran level
<i>Physical sciences (107, 1152), other (237)</i>									
<0.001	0.134	0.381	0.559	0.877	<0.001	0.09	0.359	0.645	0.823
<i>Technologies and applied sciences (228, 2350), for. ties (1777)</i>									
<0.001	0.098	0.747	<0.001	<0.001	<0.001	0.226	0.812	0.064	0.004
<i>Technologies and applied sciences (228, 2350), unique acq. (350)</i>									
<0.001	0.727	0.371	0.258	0.109	<0.001	0.661	0.461	0.191	0.062
<i>Technologies and applied sciences (228, 2350), joint acq. (859)</i>									
<0.001	0.142	0.147	<0.001	<0.001	<0.001	0.949	0.699	0.006	<0.001
<i>Technologies and applied sciences (228, 2350), repeated (522)</i>									
<0.001	0.588	0.428	<0.001	<0.001	<0.001	0.417	0.251	0.008	<0.001
<i>Technologies and applied sciences (228, 2350), co-auth. ref. (12)</i>									
0.024	0.84	1	0.407	0.904	0.024	0.822	1	0.861	0.96
<i>Technologies and applied sciences (228, 2350), faculty ref. (20)</i>									
0.001	0.844	0.978	0.993	0.94	0.001	0.842	0.999	0.999	0.98
<i>Technologies and applied sciences (228, 2350), other (26)</i>									
<0.001	0.391	0.874	0.056	0.057	<0.001	0.443	0.994	0.063	0.042
<i>SSH (869, 9380), for. ties (1798)</i>									
<0.001	0.012	0.863	<0.001	<0.001	<0.001	0.246	0.663	0.032	0.001
<i>SSH (869, 9380), unique acq. (453)</i>									
<0.001	0.366	0.424	0.019	0.005	<0.001	0.365	0.483	0.022	0.004
<i>SSH (869, 9380), joint acq. (848)</i>									
<0.001	0.034	0.369	<0.001	<0.001	<0.001	0.577	0.205	<0.001	0.001
<i>SSH (869, 9380), repeated (463)</i>									
0.001	0.506	0.972	0.586	0.415	<0.001	0.43	0.919	0.814	0.699
<i>SSH (869, 9380), co-auth. ref. (12)</i>									
0.011	0.32	0.998	0.925	1	0.01	0.298	0.967	0.995	1
<i>SSH (869, 9380), faculty ref. (23)</i>									
0.001	0.322	0.991	0.973	1	0.001	0.295	0.976	0.985	1
<i>SSH (869, 9380), other (11)</i>									
0.027	0.317	0.986	0.742	0.764	0.027	0.594	1	0.977	0.919