Research Network Emergence: Societal Issues in Nanotechnology and the Center for Nanotechnology in Society

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Abstract

This paper looks at the creation of a network of researchers of social issues in nanotechnology and the role of the Center for Nanotechnology in Society at Arizona State University (CNS-ASU) in the creation of this network. The extent to which CNS-ASU is associated with the development of a research network around the study of social issues in nanotechnology is examined through geographic mapping of co-authors and citations of center publications, network analysis of co-authors of papers on social issues in nanotechnology, and a disciplinary analysis of these papers. The results indicate that there is an extensive network of co-authorships among researchers studying social issues in nanotechnology with CNS-ASU at the center of this network. In addition, papers written by center members and affiliates integrate a diverse range of disciplines. Qualitative data are used to interpret some of the ways that citation occurs.

1. Introduction

In the emergence of a novel research domain, one epistemic goal is to create a research network to enhance exchange of information, methodologies, and data, and corroborate and synthesize findings. The intent of a research network is to go beyond any single project to foster connections among scholars working in the same broad area.

This paper examines whether and to what extent a nascent network has emerged around research on social issues in nanotechnology. The US National Science Foundation (NSF) has made major investments in two centers in this domain. From September 2005 through to August 2016, NSF sponsored the Center for Nanotechnology in Society at Arizona State University (CNS-ASU) and the Center for Nanotechnology in Society at University of California, Santa Barbara (CNS-UCSB). NSF also provided support for several smaller scale centers, individual investigator projects, and societal aspects of nanoscale science and engineering centers, materials research science and engineering centers, and other similar types of centers. But there is mixed evidence to date as to whether such investment has prompted a research network around social issues in nanotechnology to emerge.US CNS researchers have come together with researchers internationally to create the Society for the Study of Nanoscience and Emerging Technologies (SNET) to further foster international connections among researchers working on these topics. SNET has since been renamed to refer to The Society for the Studies of New and Emerging Technologies to extend beyond nanoscience. Shapira and colleagues (2010) find that in the earliest phases of social science research on nanotechnology, social scientists actually were more likely to cite works by scientists and science visionaries rather than citing works of other social scientists, thus not really behaving (at least through their citations) as if they were part of a common network. However, by the later periods, the authors found more cited references to other social scientists' nanotechnology work, as well as to social science literature in general. More recently, Shumpert and colleagues (2014) find a lack of exchange among researchers studying the ethical, legal, and social issues affecting nanotechnology (nano-ELSI) based on their analysis of nano-ELSI papers published in the 2003-2010-time period. In particular, they find that researchers form silos around particular topical areas within the domain and do not substantially work across these topics.

The work will show that CNS-ASU has played a substantial role in the emergence of a network of social science investigations into the evolution of nanotechnology. The study uses multiple methods—bibliometric analysis of social science publications concerning nanotechnology's emergence and a survey and interviews with social science researchers, managers of programs, and private sector firms. These methods converge to indicate the creation of a network of social science research into the emergence of nanotechnology, with CNS-ASU playing a prominent role in this network.

2. Background

Crane (1972) and Chubin (1972) provide early work on the role of networks in communicating the flows of research knowledge in invisible colleges. However, most new science domains do not begin at the fully-fledged research network stage, rather they typically emerge in a pre-network form (Youtie et al. 2006). A pre-network stage is marked by several different scholars' working on equivalent or comparable topics, although they may not be aware of the similarities in one another's work. Progressively, the scholars not only continue with their own work, but become mindful of the work of their colleagues and eventually recognize the benefits of exchanging information, methodologies, data, and results. Eventually social structures are created at sufficient levels to produce a nascent network. The "knowledge value collective" – comprising researchers who interrelate in the development and application of scientific knowledge – is one type of nascent network in which producers and users, even if they do not personally know one another, have sufficient awareness of using the same corpus of information and working on the same broad research goal (Bozeman and Rogers 2002, Rogers and Bozeman 2001). The extent to which this network emerges into a formally recognized research system is important for the creation of new fields of study (Youtie et al., 2006). The analysis of the emergence of scientific networks has been the subject of much study. A good deal of this literature on emerging research networks relies heavily on network analyses of large bibliometric datasets of metadata from scientific articles. Much of this work is based on analysis of direct citation of one paper by another, or on co-citation in which papers are related because they are jointly cited by other sets of papers (Boyack and Klavans, 2010). Chen (2005) summarizes the history of methods used from 1965 to 2004 to identify the emergence of new scientific topics. These studies draw on methods such as examining changes over time, co-citation networks, and networks based on sharing the same cited references (known as bibliographic coupling). Most of these methods identify and label the emerging scientific topics based on terms used in the titles or abstracts of the articles. This work has been updated in studies by Small and colleagues (2014), who apply clustering techniques to the networks to identify emerging scientific topics and benchmark them against measures such as funding awards, and Klavans and Boyack (2017), who work with a reduced set of articles with 100 or more citations.

These works do not give much consideration to the active role of policy instruments in the emergence of new scientific areas, except in the case of Small and colleagues (2014), which used funding as a check, albeit not as an instrument of study. A smaller set of works have examined the role of research centers in the emergence of a scientific area. Rogers and colleagues (2012) examined the role of nanoscale science and engineering centers in the emergence of nanotechnology research. These authors noted that although each center was funded and established separately, companies were using them in a network by establishing publication and non-publication-based relationships with multiple centers. Boardman and Corley (2008) and Ponomariov and Boardman (2010) have used survey data to show that centers lead to greater collaborations between scholars from different institutions, fields, and departments relative to a comparison group. Youtie and colleagues (2013) drew on a social network survey and analysis of bibliometric information to demonstrate how a center involving researchers from multiple institutions and multiple learning disciplines comes together in a concept called “centerness” through the sharing of knowledge about important works by eminent scholars and the sharing of methods and designs to sharpen conceptual focus. Smith and colleagues (2016) demonstrate how five Energy Frontier Research Centers increase co-authorship-based networking despite lacking formal structures for fostering collaborative research.

These studies identify an associational relationship between centers and collaborative scholarly networks, but they stop short of examining the role of the center as a hub for such networks. In this work, we examine whether and to what extent one of the CNS centers – CNS-ASU – has served as ta focal point for an emerging scientific network for connecting researchers studying and working with social issues involved in nanotechnology. The mission of CNS-ASU, according to Radatz and colleagues (2017) is to research social issues related to nanotechnology, train scholars in cross-disciplinary perspectives of studying these issues, engage various stakeholders (citizens, private sector, scientists, policymakers), and partner with research laboratories to embed social scientists for the purpose of giving consideration to social issues while the science is being developed instead of afterwards, when policy intervention might be more difficult. CNS-ASU offered a range of ways to participate in the center, from attending a workshop or public event to being trained through various modes such as an annual winter school to running a public deliberation and dialogue about the social implications of nanotechnology to leading one of the four research thrusts or two cross thrust research cluster areas of the center.

Our analysis uses a mix of bibliometric analysis to understand the scale of research network emergence and survey and qualitative analysis to understand the concepts underlying this emergence. The bibliometric analysis begins by describing the nanotechnology social science domain and what can be considered to be in and out of domain. A subsequent definitional task is to associate articles with a formal connection to CNS-ASU. After presenting basic statistics on how the CNS-ASU articles compare with the nanotechnology social science domain, we turn to an analysis of measures of connectivity across the domain based on co-authorship and citation. The analysis focuses on connections across geographical area, co-authorship network, and discipline. The results indicate that there is an extensive network of co-authorships among researchers studying social issues in nanotechnology with CNS-ASU at the center of this network. The center's publication reach expands beyond its formal geographic locations to encompass co-authors in nearly all US states and multiple countries. In addition, papers written by center members and affiliates integrate a diverse range of disciplines. Drawing from the survey and interview data set collected in parallel to the bibliographic data, we suggest that social science concepts (e.g., “anticipatory governance,” “real-time technology assessment,” “socio-technical integration”) that were developed and disseminated by the Center as a vehicle help explain the effects of center influence.

3. Method

To define the nanotechnology social science domain, we extend from the approach developed by Shapira and colleagues (2010). This work recommended that it was important to include articles from the two main indexes of scholarly articles—the Web of Science (WOS) and Scopus—to sufficiently capture social science and humanities works. It also suggested that, while on the physical and biological side, a two-stage complex Boolean search strategy was necessary to capture research on a specific scientific area that resides in the broader nanotechnology domain (see Porter et al. 2008, Arora et al. 2013), on the social science and humanities side, social scientists were more likely to use a nano-prefix term in the title or abstract if they were studying societal issues in nanotechnology, hence “nano*” was sufficient if it was followed by cleaning and removal of out-of-domain papers. We thus applied a basic nano* search term to the topic field (which includes title, abstract, and keywords) in the WOS Social Science and Arts and Humanities Citation Index (SSCI/AHCI) and to several subcategories in Scopus’s “Social Sciences & Humanities” category: (1) social sciences; (2) business, management and accounting; (3) arts and humanities; and (4) economics, econometrics and finance. This initial search was performed in March of 2013 for the time period 1990 to March 2013 resulted in 2,160 Scopus records and 1,388 WOS records. We combined these two databases using VantagePoint text mining software, removed duplicates, then undertook a significant amount of cleaning and removing of out-of-domain papers associated with the following terms in article titles: formulas/chemical compounds (i.e., $NaNO_2$, $NaNO_3$), ‘Nanook and his contemporaries’, ‘Nanon’, ‘Nanoose Bay’, colloquial uses of the phrase ‘Nano-second’, ‘Nanocephalic Aztecs’, and ‘the nanosance’, Tata’s ‘Nano’ car, Apple’s Nano products, certain out of scope journals. We also manually reviewed the records based on their titles and abstracts to remove any out-of-domain publications not picked up by the aforementioned exclusion keywords. This process resulted in a dataset of 1,760 nanotechnology publications of which 63% (1,116) come out of WOS and the remainder out of Scopus.

How did we determine whether or not a publication was associated with CNS-ASU? Two approaches were used. First, we matched a list of journal articles obtained from the center with this dataset. Sixty percent of these articles were found in our database; the primary reason for missing listed articles is that they were white papers, under review, or books or book chapters not indexed by the two sources we used. Matching listed publications provided the most direct link, especially for investigators receiving monetary support from the center, but it underreported articles published with non-monetary support from the center by affiliates who received benefits through other means such as access to data, concepts, or methods. These two methods resulted in 292 publications associated with the center (285 plus another seven "pre-center" publications that provided an intellectual basis for the creation of the center). Of these, 78% (230) came out of WOS.

After providing basic statistics on the growth of publications and citations, we use multiple methods to analyze the extent of collaboration in center versus domain wide publications. Co-authorships are examined through GIS mapping and network analysis. Cross-disciplinary connections are illustrated using the map of science and measures of diversity and integration. Maps of science use a base map produced from the (cosine) similarities of cross-citations of articles in journal categories; underlying dimensions representing "disciplines" are obtained through factor analysis using the 19 factor solution and the results are projected into a two-by-two network map with the 19 factors shown as labels and colored nodes (Rafols et al. 2010). The diversity and integration scores also are based on WOS categories of journals (Porter and Rafols 2009, Porter et al 2007, Porter et al. 2008). Diversity measures "disciplinary" differences in the types of journals in which an author or organization publishes, where disciplines are proxied by WOS categories; diversity scores range from near zero (publishing in a very disciplinarily diverse array of journals) to one (all in a single disciplinary category of journals). In contrast, the integration score reflects the disciplinary areas of the cited references in one or more papers and ranges from near zero (references from a single disciplinary area) to one (references from very different disciplinary areas). Because of the orientation of these measures around WOS categories, the maps of science and integration and diversity scores only operate on the WOS data subset.

As part of the center assessment, this bibliometric study was conducted in parallel with other assessment research methods. A survey of center participants was administered in April and May of 2013 to all 798 participants in the center's organizational database, where the minimum threshold for inclusion was attendance at a center meeting or event. The response rate to this survey was 51.3% (440 respondents). A subset of respondents (n=80) was selected for qualitative interviews with the aim of examining the quality and types of center impacts and outcomes (for further details, see CNS-ASU, 2015, 107-109; Radatz et al., 2017). Selection to participate in qualitative interviews was based on an effort to cover the range of stakeholders who were active with the center for more than one year, from research thrust leaders of the center to students who were trained through the center to nanotechnology entrepreneurs and policymakers who took part in center workshops. These instruments explored the ways in which participants related to the center and helped to shed light on publishing and co-author data. The survey and interview work also dealt with cross-sectoral impacts. Cross-sectoral participants are most easily defined for the purposes of this (bibliometric) study as persons outside academia who do not publish or cite publications but who are in some way related to NSE (publics, stakeholders) and the outreach work of the Center. We draw on these findings where relevant to help in interpreting the results of our bibliometric analysis.

4. Results

In our bibliometric database of nanotechnology social science publications, CNS-ASU papers account for more than 10% of works on social issues in nanotechnology. The number of CNS-ASU papers in 2012/13 is more than two and a half times the number in 2006. (We add data for the first three months of 2013 into the 2012 totals to account for time lags in reporting publications for a given year.) The set of non-center affiliated papers also grew, from a much larger base, by 1.3 times over this same period. A normalized growth chart, which accounts for these scale differences by dividing both subsets by the number of papers in 2006, shows that the growth of center papers tracks non-center papers, albeit at a slightly lower but with an upward inflexion point at 2010 (Figure 1). The inflexion point suggests that some time is required for center organization, data collection, and paper writing in the social sciences before a substantial quantity of papers can be expected. More important, however, than the absolute number of papers is their impact. Here we find that CNS-ASU papers accounted for 14% of all citations to nano-social science works.[1] This level of citation is almost one-third higher than can be expected based on the center's share of papers. Put another way, on average, center publications attracted relatively more citations than was the case for the nano-social science dataset writ large.

[FIGURE 1]

We now turn to center's influence on co-authorship. One way to view this influence is by observing the geographic reach of co-authors of center affiliates and researchers engaged in nano social issues publishing. We extracted the affiliation of co-authors of CNS-ASU, geocoded the addresses of these organizations, and added this x-y data to a geographic base map using ESRI mapping software. The resulting map uses a combination of methods to show the geographic reach of the center (Figure 2). Forty-five of the 50 US states have societal researchers focused on nanotechnology. Of these, 29 have co-authored publications with CNS-ASU researchers and affiliates. Thus CNS-ASU has a significant geographic presence across the US. But not only does the center's research reach across the US; center papers include co-authors in 22 countries, with the top co-authoring countries including the United Kingdom (51 papers), Netherlands (38), China (17), and Germany (14). The magnitude of CNS-ASU's presence is indicated by the size of the nodes on the map, where each node represents the cities of institution's with which center co-authors are affiliated. Although CNS-ASU is headquartered in Tempe, Arizona, and has major partnerships in Atlanta and Madison, Wisconsin, nodes are also observed in Washington, DC, Minneapolis, MN, Charlottesville, VA, Columbia, SC, Ithaca, NY, Raleigh, NC, and

[1] We do not control for self-citations because we are looking over a multi-year time horizon and at a macro-level rather than an individual article or author level. See (Rousseau 1999; Aksnes 2003; Glanzel and Thijs 2004)

Santa Barbara, CA. In essence, the center has a geographic influence that extends far beyond its headquarters and main partner locations.

[FIGURE 2]

We undertook a social network analysis to pursue further examination of the center's co-authorship collaborations. This analysis is based on all nano social science authors with at least two publications in our dataset, for a total of 467 authors. These data were imported into Gephi network graphing software and a ForceAtlas2 layout (for small to medium-sized network graphs) applied with label adjustments to remove overlaps. Nodes (i.e., authors) representing the work of senior members of CNS-ASU are colored "blue," student and affiliated members are represented by the red nodes, and non-affiliates are presented by the green nodes (Figure 3). Senior members make up 3% of the nodes/authors, students and affiliates 16%, and the remaining 81% are non-affiliates. Links between the nodes represent the number of co-authored papers.

[FIGURE 3]

The resulting network has several characteristics of a dispersed configuration of authors. The network diameter is relatively extensive at 13 and the network is not very dense (at 0.005). At the same time, notwithstanding this wide configuration of authors, evidence of coherence also exists. For example, 40% of the nodes are in connected components or sub-communities of researchers and the number of links with other co-authors across the whole network is represented in an average degree of 2.3. In addition, the network gives rise to evidence of a center or hub. Although no effort was made to manually impose CNS-ASU into a central position in the network map, CNS-ASU senior authors occupy a central position in the network. Senior CNS-ASU authors have more than 3.5 times the degree centrality (7.3) and 20 times the betweenness centrality (1136) of non-CNS-ASU authors (at 2.0 and 54 respectively). In sum, the co-authorship network represents an extensive connection of authors which have, at their nucleus, senior CNS-ASU authors. One interpretation of apparent central role of CNS-ASU is that it represents a core-periphery effect with a denser central location populated by CNS-ASU authors (Borgatti and Everett, 2000).

Finally, we sought to understand the extent to which the center brings together work from different disciplines. We used visual maps of science and diversity and integration scores to represent these results (Rafols, Porter, and Leyersdorf, 2010). The results show that the diversity and integration scores between the center and non-center publications are not that different. CNS-ASU papers are published in slightly less diverse types of journals than non-center papers (0.63 for CNS-ASU versus 0.56 for non-center). However, the typical (average) center paper does a little better at integrating research from diverse disciplines in its cited reference list than does the typical non-center paper (0.69 versus 0.62). In essence, published works in dealing with nanotechnology's societal issues integrate a very diverse set of papers. Moreover, we find that physical and biological science papers are aware of and cite CNS-ASU articles. Indeed, 35% of the citations of CNS-ASU articles are by physical or biological science articles. This pairing of a relatively focused set of journals submissions incorporating a diverse set of works is shown through a comparison of maps of science (Figure 4). Center researchers most commonly publish in business and management (e.g., management, communications, ethics, business, information science), health and social issues (e.g., history and philosophy of science, medical ethics, public, environmental, occupational health), social science (e.g., planning and development, law, social science – mathematical models), biomedical sciences (e.g., multidisciplinary science – i.e., where the journals *Science* and *Nature* are classified) and materials science (e.g., materials science, nanoscience and nanotechnology). The cited references used in these articles, of which there are many more scalewise (i.e., each paper has about 38 cited references on average), shows an even broader coverage of disciplines. Cited references to works in materials science, biomedical science (i.e., articles in *Science* and *Nature*), and mathematics and engineering continue, but the maps also show much more citing of other works in social science, business and management, and economics, politics and geography disciplinary areas. Indeed, 88% of center papers cite other social science or psychology works and this category makes up more than half of the references in center papers. Physical science and engineering works are the next most prevalent, cited in 84% of center papers and comprising 42% of references. The third most common category of references is biology and medicine (cited in 55% of center papers and comprising 12% of references). The prevalence of social science integration with the physical/material sciences as compared with biology/medicine is noteworthy. Usually the divide between social and physical/material science is more difficult to cross: larger scale overall global mappings of science indicate a more prevalent connection between the social sciences and medicine/biology (Rafols et al. 2009).

[FIGURE 4]

Qualitative research yielded a further set of insights, building on the findings of the bibliometric data analysis. We observed several qualitative results: (1) the *general* integrative influence of the center largely occurred via the social science concepts that it developed and disseminated in an interdisciplinary setting ("concept work"); (2) the *specific* integrative influence of center concepts took the form of either (2a) an innovative framework by which practical social science concerns are included in nanoscience research or (2b) a proof of concept at largescale for those already familiar with center concepts (and for those familiar with integrating social sciences with natural and physical sciences); furthermore, these are (3) *subtle* effects that may not show up in the bibliometrics but indicate use of CNS-ASU knowledge. As per above, (4) it is noteworthy that there is a *link* between social scientists and physical/natural scientists (usually, this "disciplinary divide" is much weaker). Interviews and survey responses help us understand the role of the center in bringing about these atypical and noteworthy results.

The survey (Radatz et al., 2017) measured the influence of the center in part by asking whether participants were influenced more by concepts or skills/methods. Participants in center activities comprised a diverse range of scholars (and in some cases non-academic professionals such as entrepreneurs or informal science educators), for many of whom specific social science skills and methods were either not necessary for their work or were something with which they already had proficiency from an earlier period in their career. The results show that participants were most influenced by the conceptual work of the center. This suggests a fairly wide impact of the center as a concept generator and disseminator (See Table 1 and 2). Key concepts were likely to have been relevant to a more diverse set of participants, and thus perhaps center publications were more understandable and usable (citable) to a broader range of disciplines, even those outside of the social sciences. Concept use was also measured. A significant percentage of users indicated concept use in ‘research’, which may parallel some of the bibliometric measurement of CNS-ASU influence. As shown in Figure 5, however, ‘Reported use of various concepts by use type’, a variety of concepts were deployed in diverse settings (e.g., ‘teaching’, ‘professional life/work’, ‘public communication’, and ‘other’), indicating a broad impact of concepts beyond the citation sphere of measurement.

[Table 1]

[Table 2]

For many respondents, the conceptual framing of nanotechnology in societal terms seemed to be seen as innovative and hence citable. For others, the center warranted their attention not for its innovativeness, but for its ability to demonstrate the practical application of those concepts. This was particularly so for professional social science participants who were only loosely associated with the center but who were active within the field of social science of science and technology and who were broadly aware of the conceptual background from which the center emerged. For example, many in the European science and technology studies (STS) community saw the center as an illustrative example of pre-existing conceptual claims in their field being put into practice – in other words, it represented a proof of concept even if (within the field) they did not find the concepts particularly new. As one European scholar commented:

> *… CNS, they made visible to actors in Europe, that there was a societal reflection on nanotechnology and [convergent] technologies in America. I think that’s very important.*

“Real-time technology assessment,” a foundational concept for the center, was demonstrated in the survey results to have been widely recognized by the center participants. It was considered by this [European] group to have been an innovative adaption of previous work in technology assessment, i.e. constructive technology assessment (Rip, et al. 1995), to the specifics of the American context and the specifics of a large-scale social science research center, but not a fundamentally unprecedented conceptual development in their field. These persons reportedly would occasionally cite the work of CNS-ASU and thus would show up within the citation analysis data in this study. The interview analysis gives us some idea of how citation (and concept transfer) is utilized in particular researcher contexts. These qualitative results thus suggest why two subgroups cited CNS-ASU work, namely (2a) as an innovative framework and (2b) as an example of successfully applied social science conceptual work. Thus, the qualitative work here helps explain *why* some of the citations may have occurred in the first place and hence point to the integrative role of the center.

Interestingly, not all center influence shows up in citation studies. To give an example, some environmental sciences researchers reported choosing to frame a publication on nanoparticle distribution around the likely social relevance of their results, choosing to name specific consumer products likely to be eaten by children. One environmental science researcher interviewed said:

> *I don't know if it's CNS, but I feel like we have at least a reason that we try to do some things to impact society rather than just building the latest widget or—in environmental nanotechnology, people look at how two nanoparticles interact with a river, and that's what they do. We try to understand where these nanomaterials have come from, how—from different consumer products.*

In this particular case, the key publication did not cite any CNS-ASU research so it would not show up on a citation analysis. But it does suggest the possibility of a more diffuse, indirect effect on scientific publication because of interdisciplinary collaboration with social scientists. The influence of concept work, formulated for broader communities of researchers who previously had never considered societal/science interactions, was in many cases shown to be influential

The qualitative findings suggest that the Center's social science concept work appealed to a more general audience because such work was interesting, relevant and innovative and because it was more accessible and transferred well to their own more specific settings. For example, a conceptual emphasis on practical social science engagement with scientific workers and other stakeholders in nanotechnology research was relevant to a broader range of disciplines, although valued within the original social science community for perhaps different reasons. Specifically these social science concepts could be used by scientists, engineers and even non-academic professionals, although they were less likely to be used as a value in themselves (in the way that a social scientist might cite another social scientist's work because they are talking directly about the concept) but in two other ways: 1) as the framing concept for facts about nanotechnology that were thought to be relevant, usually a fact that informed their thinking or perhaps future research choices, but was not considered within the epistemological remit of their discipline (for example a public opinion survey on nanotechnology with results considered surprising to the scientists); and 2) as the framing concept for new choices in a research topic. Demonstrating the first situation (concept as frame for fact transmission), one informal science education professional discussed the balance of their interests in CNS-ASU concepts and methods:

> *They [CNS-ASU] did work comparing what scientists thought about things with what the public thought about things…which led us to a whole bunch of other things that we've ended up doing here, doing here programmatically. That's not so much about a certain research technique. It's more about a research result.*

The example above of environmental engineers researching the topic of consumer foods, chosen because this was societally relevant (rather than because of a specific question within environmental engineering epistemology) is an example of a concept being used to frame research choices. While in some cases this type of influence may show up within a citation analysis, in many cases it may not.

5. Discussion

The greater part of the evidence presented in this paper suggest that CNS-ASU has the characteristics of being associated with the creation of a network of societal research on nanotechnology. The center has wide geographic reach in its co-authorships and in who cites its research papers. While this outcome does not necessarily mean that the center has established a formal knowledge value collective, indeed this result may well be outside of the scope of the center's remit, it does suggest extensive and active knowledge sharing through co-authorship and publication. The network analysis shows that center senior members are the hub of the co-author network of researchers in the nano-social issues co-authorship domain, suggesting that its influence extends beyond mere connectivity to importance to keeping the network anchored together, which is important for a loosely connected system. From a subject matter viewpoint, the center's own publications integrate works from other social science as well as physical and biological science domains.

On the other hand, there are limitations to what these measures signify for the effect of the center in terms of creating a research network. The network map suggests that social science researchers of nanotechnology remain a loose configuration of investigators with the majority not integrated into a sub-community. The comparison group has about the same diversity and integration scores as does the center. Thus the center's scores may simply reflect standard practice in the social science research (to integrate various disciplines as part of the analytical process) rather than a particular integrativeness attribute of the center (Hicks 2005). In addition, the geographic impact of the center may be indicative of an organization's having sufficient scale and resources to support a large body of research rather than that the center created a national research network of social scientists per se. Indeed, other CNS-ASU activities may have more of a role in national network creation such as the center's work with science museums, scenario congresses, and an associated socio-technical integration research project where social scientists learn capabilities to engage with physical and biological scientists in their laboratories on issues with societal implications (Fisher et al., 2010).

The method we used also has limitations. We do not isolate particular concepts within nano social science and observe the development of co-authorship and other forms of collaboration around these particular concepts. From the parallel qualitative data we have shown that concept work was a strength of the center. Some saw the conceptual linking of physical/material science and social science issues as innovative (for example many physical scientists) while others saw in the center a proof of concept, that this conceptual linking could be made to work in practice, that the US had large-scale social science research centers that were doing just this, and in this way contributing to the global conversation on nanotechnology. We have noted that while concepts formed a vehicle for center influence not all impacts of interdisciplinary collaboration and influence would show up as citation and some disciplinary citation does not indicate unprecedented conceptual innovation. Often specific factual findings (rather than concepts) were relevant to those who cite or are influenced. Becoming aware of societal relevance in scientific choices may have altered laboratory research selections. This is to say that in many cases the center's conceptual framework effectively serves to organize the research agenda or make the interpretation of findings societally relevant. In some cases, this influence detected in the qualitative data may not be entirely measureable by these bibliographic methods.

Our research is focused around only one of the two US societal nanotechnology centers so we are not able to present the full picture of the joint effects of these centers. While the two centers had some overlap, they maintained different emphases. For example, CNS-UCSB paid significant attention to risk, which we may be underrepresenting in our database by not having the center-specific information from CNS-UCSB, as well as from other nanotechnology center and project investments. However, to this point, our paper does use a fairly broad bibliometric definition of nanotechnology through the application of the nano-prefixed term, which we feel takes a broadly inclusive approach to capturing nanotechnology publications concerning societal issues.

Although we cannot establish, without question, a causal connection between CNS-ASU and the emergence of network characteristics, with limitations noted we do see evidence of the formation of a network around the societal study of nanotechnology's rise. CNS-ASU emerged as a cross-geographical collaborator, network hub, and integrator of research on the societal aspects of nanotechnology. These characteristics signal that an emerging network for researching societal concepts in nanotechnology has developed.

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References

Aksnes, D. (2003). A macro study of self-citation. *Scientometrics*, 56(2), 235–246.

Arora, S. Porter, A.L., Youtie, J., Shapira, P. 2013. Capturing new developments in an emerging technology: an updated search strategy for identifying nanotechnology research outputs. *Scientometrics* 95 (1), 351-370.

Boardman, P. C., & Corley, E. A. (2008). University research centers and the composition of research collaborations. *Research Policy*, *37*(5), 900-913.

Borgatti, S. P., & Everett, M. G. (2000). Models of core/periphery structures. *Social networks*, *21*(4), 375-395.

Boyack, K. W., & Klavans, R. (2010). Co-citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately?. *Journal of the Association for Information Science and Technology*, *61*(12), 2389-2404.

Bozeman, B., Rogers, J., 2002. A churn model of scientific knowledge value: internet researchers as a knowledge value collective. *Research Policy* 31, 769–794.

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the Association for Information Science and Technology*, *57*(3), 359-377

Crane, D. (1972). *Invisible colleges; diffusion of knowledge in scientific communities*. Chicago: University of Chicago Press.

Chubin, D. 1985. Beyond invisible colleges: Inspirations and aspirations of post-1972 social studies of science. *Scientometrics* 7 (3-6): 221-54.

CNS-ASU, Annual Report for the Period September 1, 2014 to August 31, 2015. Center for Nanotechnology in Society at Arizona State University. http://cns.asu.edu/sites/default/files/library_files/annual_report_for_award_0937591_2015_04_15_without_financials.pdf

Fisher, E., Biggs, S., Lindsay, S., & Zhao, J. (2010). Research thrives on integration of natural and social sciences. *Nature*, *463*(7284), 1018-1018.

Glanzel, W., & Thijs, B. (2004). The influence of author self-citations on bibliometric macro indicators. *Scientometrics*, 59(3), 281–310.

Hicks, D. (2005). The four literatures of social science. In H. Moed, W. Glanzel, & U. Schmoch (Eds.), *Handbook of quantitative social science and technology research* (pp. 473–496). Netherlands: Springer.

Klavans, R., & Boyack, K. W. (2017). Which type of citation analysis generates the most accurate taxonomy of scientific and technical knowledge?. *Journal of the Association for Information Science and Technology*, *68*(4), 984-998.

Ponomariov, B. L., & Boardman, P. C. (2010). Influencing scientists' collaboration and productivity patterns through new institutions: University research centers and scientific and technical human capital. *Research Policy*, *39*(5), 613-624.

Porter, A. L., Cohen, A. S., Roessner, J. D., & Perreault, M. (2007). Measuring researcher interdisciplinarity. *Scientometrics*, *72*(1), 117-147.

Porter, A. L., & Rafols, I. (2009). Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. *Scientometrics*, *81*(3), 719-745.Porter, A. L., Roessner, D. J., & Heberger, A. E. (2008). How interdisciplinary is a given body of research?. *Research Evaluation*, *17*(4), 273-282.

Porter, A.L., Youtie, J., Shapira, P., Schoeneck, D. (2008). Refining search terms for nanotechnology. *Journal of Nanoparticle Research*, 10(5), 715-728.

Rafols, I., Porter, A.L., Leydesdorff, L. (2010). Science overlay maps: a new tool for research policy and library management, *Journal of the American Society for Information Science & Technology* 61(9), 1871-1887.

Radatz, A., Reinsborough, M., and Fisher, E. (2017). Engaged Social Science Research into Nanoscale Science and Engineering Communities: An Assessment of the Center for Nanotechnology in

Society at Arizona State University. Working Paper. Tempe, AZ: Center for Nanotechnology in Society, Arizona State University.

Rip, A. and Schot, J.W. and Misa, T.J. (1995) *Managing Technology in Society*. *The Approach of Constructive Technology Assessment.* Pinter Publishers, Londen, New York.

Rogers and Bozeman (2001). "Knowledge Value Alliances": An Alternative to the R&D Project Focus in Evaluation, *Science, Technology, & Human Values* 26(1), 23-55.

Rogers, J. D., Youtie, J., & Kay, L. (2012). Program-level assessment of research centers: Contribution of Nanoscale Science and Engineering Centers to US Nanotechnology National Initiative goals. *Research Evaluation*, *21*(5), 368-380.

Rousseau, R. (1999). Temporal differences in self-citation rates of scientific journals. *Scientometrics*, 44(3), 521–531.

Shapira, P., Youtie, J., & Porter, A. L. (2010). The emergence of social science research on nanotechnology. *Scientometrics*, *85*(2), 595-611.

Shumpert, B. L., Wolfe, A. K., Bjornstad, D. J., Wang, S., & Campa, M. F. (2014). Specificity and Engagement: Increasing ELSI's Relevance to Nano–Scientists. *NanoEthics*, 1-8.

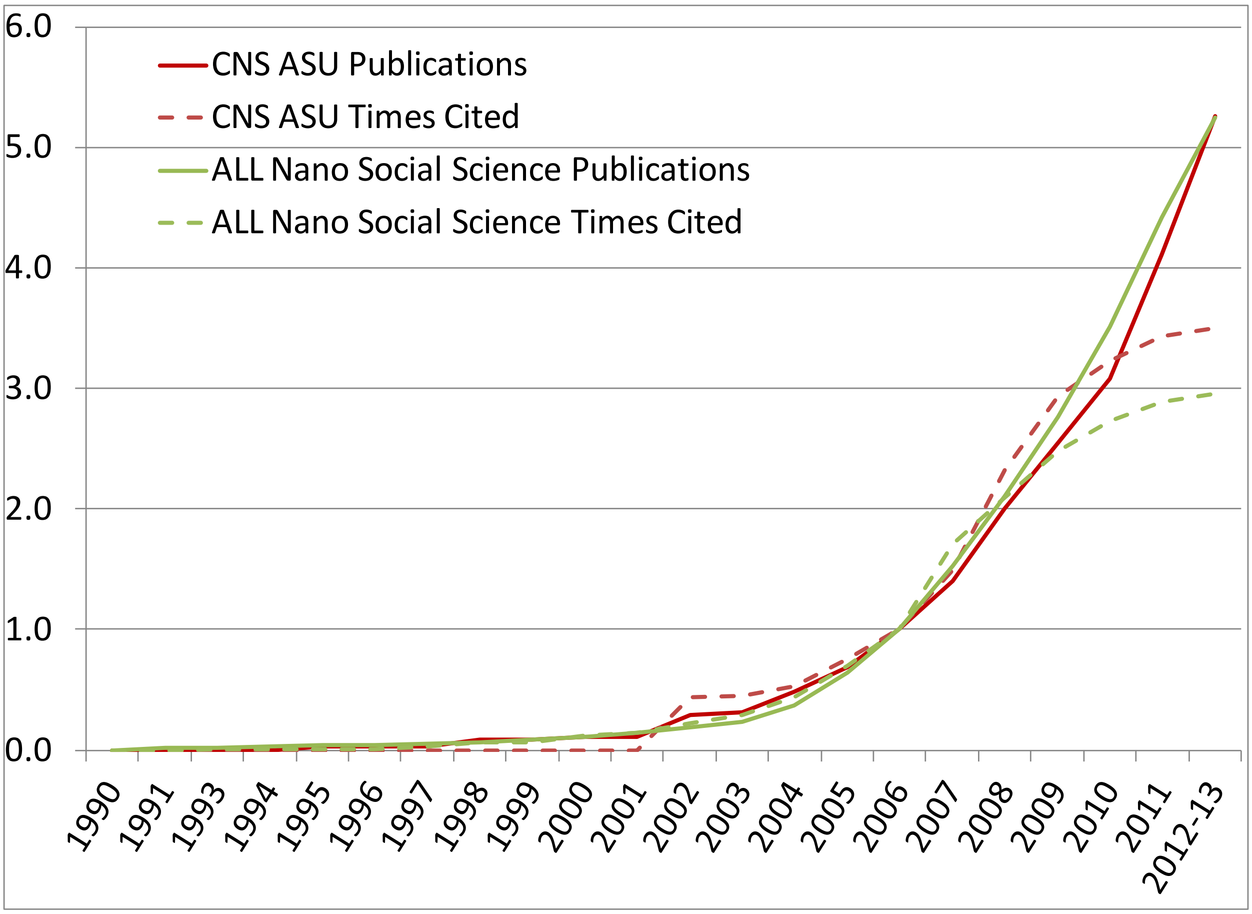
Small, H., Boyack, K. W., & Klavans, R. (2014). Identifying emerging topics in science and technology. *Research Policy*, *43*(8), 1450-1467.

Smith, A. M., Lai, S. Y., Bea-Taylor, J., Hill, R. B., & Kleinhenz, N. (2016). Collaboration and change in the research networks of five Energy Frontier Research Centers. *Research Evaluation*, *25*(4), 472-485.

Youtie, J., Libaers, D., & Bozeman, B. (2006). Institutionalization of university research centers: the case of the National Cooperative Program in Infertility Research. *Technovation*, *26*(9), 1055-1063.

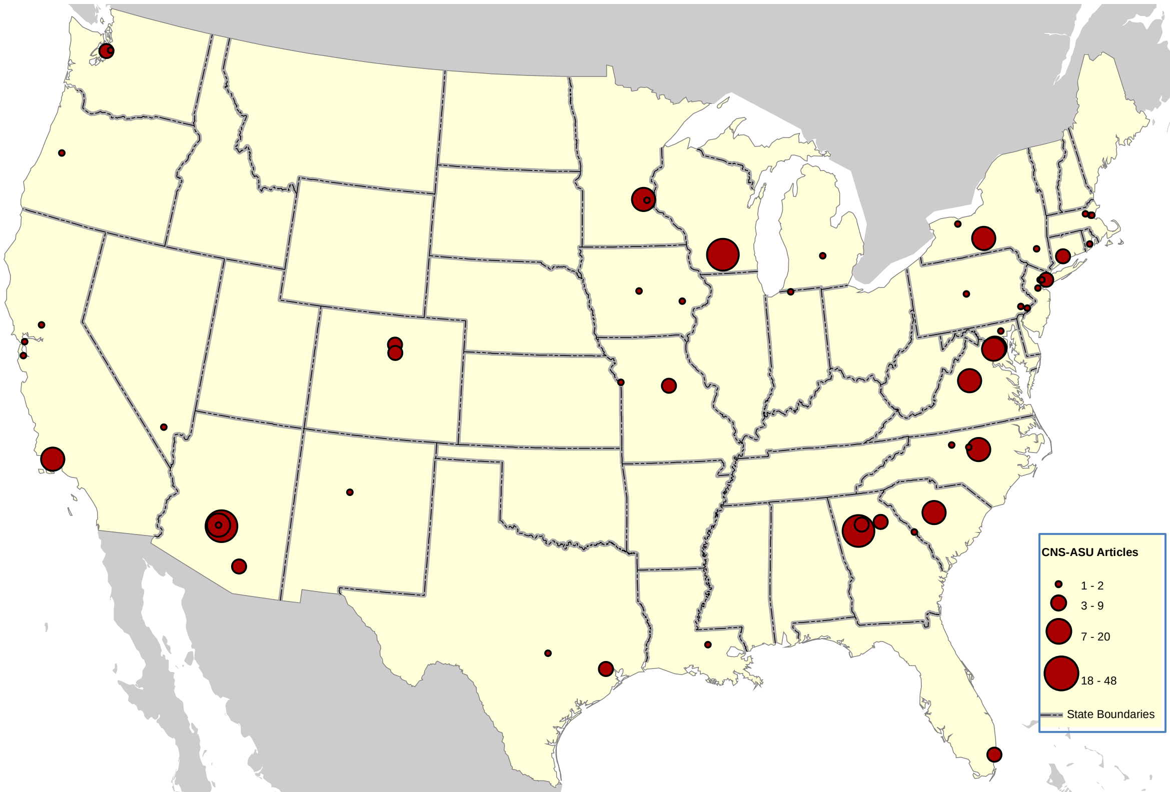
Figure 1. Publication Output, Citations: CNS ASU and All Nano Social Science

(normalized, year 2006=1)



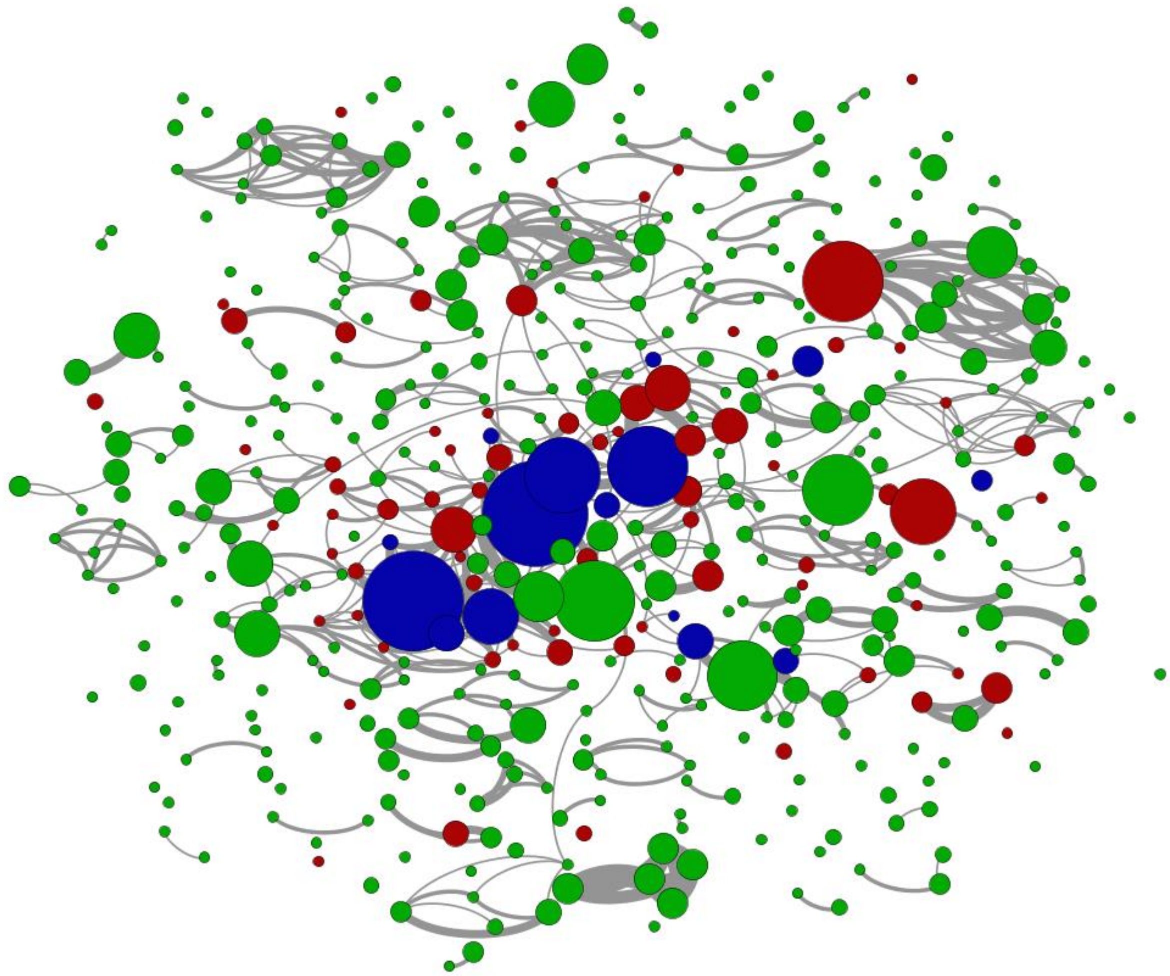
Source: Youtie, Carley, et al., 2013. N=1760 nano social science publications, 1990-2013 (March).

Figure 2. CNS ASU Articles: co-authors by states



Source: 292 CNS-ASU co-authored publications appearing in Web of Science and Scopus. CNS ASU co-author, citing author locations for co-terminus US. 29 US states represented.

Figure 3. CNS ASU Core and Affiliates Prominent in Nano Social Science Co-authorship Network

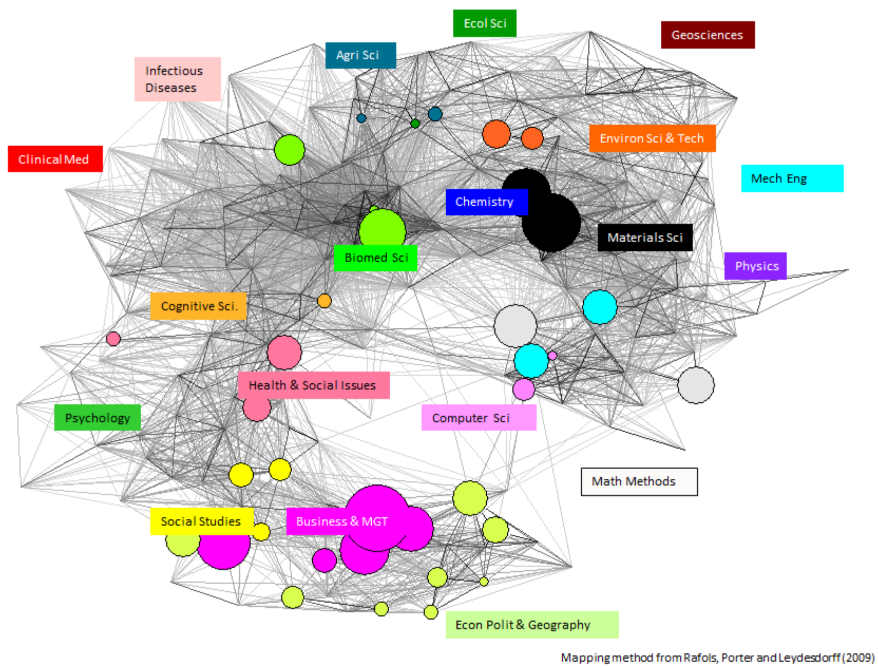


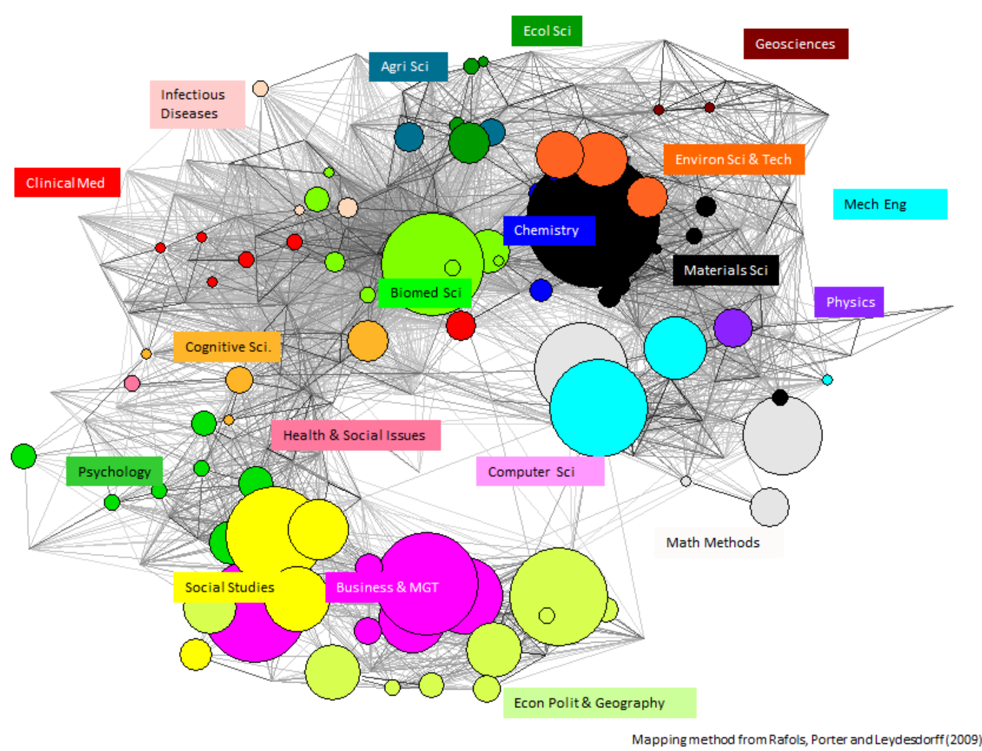
Not CNS-ASU (81%)
CNS-ASU Affil. (16%)
CNS-ASU Senior (3%)

Nodes=publication counts; edges=co-authorship counts, 2+ co-authors shown. Average degree=2.34; Network Diameter=13; Graph Density=.005; Connected Components=186 (40%); Average betweenness centrality=111.92. Caution should be taken when interpreting the disconnected components given that the position of the nodes is irrelevant to the structure of the graph.

Source: 1760 publications 1990-2013 (March), 467 authors with 2+ publications from Web of Science and Scopus.

Figure 4. Overlay of CNS-ASU publications and citations to publications





Note: Global Map of Science, 2010 update, 224 Web of Science Categories.

Table 1. CNS-ASU participant familiarity with center concepts.

Question 3. Please select any of the concepts with which you are familiar. Select any of which you are already aware and roughly understand the definition. Select all that apply. I am familiar with:

Anticipatory governance - *anticipating possible future scenarios for technology development, engaging the public in considering these, and integrating societal concerns into the development and governance of new technologies.*

Real time technology assessment - *steering innovation toward socially desirable goals by examining it and intervening as the research is being conducted.*

Public values mapping - *identifying the expected civic values of public policy (determined from public opinion, government policy statements), tracking their implementation in science policy, their evolution in practice and the ultimate social outcomes.*

Futures thinking and scenario planning - *using a variety of methods to imagine possible outcomes of a future technology, using scenarios to consider effects upon different stakeholders and how they will act.*

Responsible innovation - *considering the social and ethical implications of innovation during the design process and adjusting design accordingly.*

Sociotechnical integration - *incorporating alternative experts, methods, and perspectives into science and engineering research programs, for example, embedding a humanist in a laboratory or engaging the public in an engineering design process.*

		#
Valid Responses	Anticipatory governance	302
	Real time technology assessment	254
	Public values mapping	209
	Responsible innovation	313
	Futures thinking	282
	Sociotechnical integration	256
Missing	Did not respond[a]	20
	Did not proceed to section	24
Total		440

Source: Survey of CNS-ASU center participants, 2013 (Radatz et al., 2017). Note: a. Indicates respondent proceeded to section, but they did not respond to the question. Since this was a multiple response question and since it did not have a “None of the above” option, these participants either chose not to respond, or were not familiar with concepts.

Table 2. CNS-ASU participant use of center concepts

Question 4 A. Please select any of the ways in which you use these concepts. Select all that apply.

		Anticipatory Governance		Futures Thinking		Public Values Mapping		RTTA		Responsible Innovation		Sociotechnical Integration	
		#	Valid %	#	Valid %	#	Valid %	#	Valid %	#	Valid %	#	Valid %
Valid Responses	Professional life/work	136	49.6	129	52.2	61	39.4	102	46.8	166	59.7	111	50.7
	Research	176	64.2	147	59.5	93	60.0	134	61.5	157	56.5	135	61.6
	Teaching	97	35.4	87	35.2	37	23.9	63	28.9	101	36.3	81	37.0
	Public communication work	92	33.6	69	27.9	41	26.5	51	23.4	87	31.3	63	28.8
	Other	24	8.8	27	10.9	19	12.3	23	10.6	26	9.4	21	9.6
Missing	No response, despite familiarity[a]	28	--	35	--	54	--	36	--	35	--	37	--
Total		302		282		209		254		313		256	

Source: Survey of CNS-ASU center participants, 2013 (Radatz et al., 2017). Note: a. These participants did not respond to this question, despite indicating that they were familiar with the concept. These participants are either A. Familiar with the concept, but don't use the concept or B. they chose not to answer the question.