Final Evaluation Report

Process and Early Outcomes Evaluation of the Physical Sciences – Oncology Centers (PS-OC) Program

Reference Number: 10-2012-M NCI

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1. Introduction

A combination Process/Outcome Evaluation of the Physical Sciences-Oncology centers (PS-OC) Program was initiated and performed in the first three years of program operation to assess program performance and to promote positive adjustments of the current program and future phases. Based on an initial needs assessment at the kick-off of the PS-OC Program, the Science and Technology Policy Institute (STPI) determined appropriate study questions, performance measures, data collection methods, a logic model, and process/outcome evaluation plan. This plan was implemented by the Office of Physical Sciences - Oncology (OSPO) in collaboration with Discovery Logic, a Thomson Reuters company.

1.1 Program Overview

To further explore how the National Cancer Institute (NCI) could more effectively engage the physical sciences in cancer research, three strategic "Think Tanks" were convened during 2008 to bring together thought leaders from the fields of physical sciences and engineering with leaders in the fields of cancer biology and clinical oncology.

Four general themes emerged from these NCI-sponsored strategic think tanks as new areas of investigation for the Physical Sciences-Oncology Centers (PS-OC) program that are critical to understanding and ultimately controlling cancer:

- Physics (the Physical Laws and Principles) of Cancer: Defining the role(s) of thermodynamics and mechanics in metastasis and determining how this knowledge might be employed in new intervention strategies.
- Evolution and Evolutionary Theory of Cancer: Developing a comprehensive theoretical inclusive construct that would provide a foundation for understanding and predicting cancer heterogeneity.
- Information Coding, Decoding, Transfer, and Translation in Cancer: Pursuing theoretical and supportive experimental approaches that define what information is and how it is decoded and managed in terms of cell signaling and contextual information translation in cancer.
- De-convoluting Cancer's Complexity: Pursuing theoretical and experimental approaches from the physical sciences to cancer complexity that will inform a new fundamental level of understanding of cancer that may facilitate prediction of viable pathways to develop novel interventions.

As a first step of this initiative administered through the NCI Center for Strategic Scientific Initiatives (CSSI), a program consisting of a virtual network of PS-OCs was launched in the fall of 2009, as one of NCI's signature projects. The management of the network involves a cooperative agreement collaboration between an NCI project team, the awarded center principal investigators, and the PS-OC Steering Committee. The PS-OC Program uses the U54 mechanism, with approximately $30.1 million going to the Network in FY 2009 to achieve thematic balance across the PS-OC Network (8 appropriated U54s for five years, and 4 American Recovery and Reinvestment Act of 2009 (ARRA) U54s for two years).

Each of the twelve PS-OCs brings together expert teams from the fields of physics, mathematics, chemistry, and engineering in conjunction with researchers in cancer biology and clinical oncology to assemble and develop the infrastructure, capabilities, and research programs required to enable team research to converge disciplines of physical sciences/engineering with cancer biology/oncology. The unique structure of the PS-OC supports ongoing innovation and collaboration through funding new pilot projects, outreach projects, and trans-Network projects each year with the PS-OCs.

1.2 Program Goals

The primary objective of the PS-OC Program is to unite the fields of physical science with cancer biology and oncology to assemble trans-disciplinary teams and infrastructure to better understand the physical and chemical forces that shape and govern the emergence and behavior of cancer at all levels.
This program will foster the coordinated, iterative, trans-Network development and testing of innovative, perhaps non-traditional, approaches to understanding cancer processes, and new fields of study based on knowledge of both biological and physical laws and principles that define normal and tumor systems at all length scales. This, in turn, will cultivate paradigm-shifting science leading to exponential progress against cancer.

Overall Goals of the PS-OC Network

- Establish an unprecedented network of centers and trans-disciplinary teams focused on solving cancer problems
- Train a new generation of trans-disciplinary scientists in the area of physical sciences in oncology
- Develop innovative (assumption challenging) physical sciences-centered experimental approaches to gain new knowledge of cancer initiation and progression
- Develop and test new hypotheses/theories/models in cancer research
- Collaboratively disseminate information to the cancer research communities and the public

The extent to which each of these goals has been realized, how they were realized, and to what effect, are all relevant to the outcome evaluation performed.

2. Evaluation Purpose and Objectives

In December of 2009 and January of 2010, the Science and Technology Policy Institute (STPI) interviewed Center Principal Investigators (PI) and Senior Investigators (SI) of eight of the newly awarded PS-OCs. Areas of discussion included the grant application process, areas of research for their centers, infrastructure, communication between OPSO and the center, collaborations, and potential challenges. In March of 2010, STPI submitted an outcome evaluation plan.

2.1 Initial Interviews and Needs Assessment

STPI broke the evaluation plan into three components, prospective evaluation, structured evaluation, and summative evaluation (Figure 2.1). Currently, the program evaluation is still in the "prospective data collection" stage (Component 1). By continually analyzing and examining various types of data for correlative properties program officials were uniquely able to give a "play-by-play" analysis of the Program. This process involved a unique amalgamation of prospective data collection, interactive

evaluation, and impact evaluation. An interactive evaluation implies heavy involvement of the program officials, as has been and continues to be the case here. The next step is a structured evaluation via expert panel, which falls under impact evaluation which is being used to analyze the effects of an existent program (Component 2). The third and final part of the evaluation plan is to perform a summative (full outcome) evaluation after 10+ years have passed since the start of the program (Component 3).

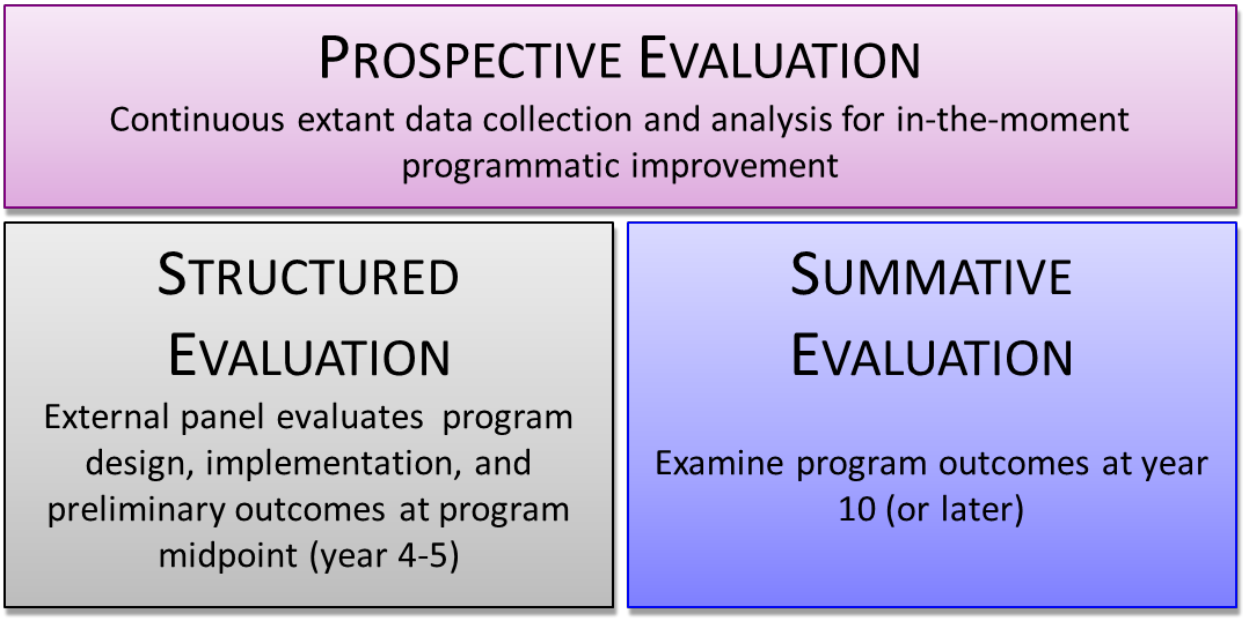

Figure 2.1. Graphic representation of STPI Evaluation Plan over time.

2.2 Logic Model

The intent of the PS-OC Process/Outcome Evaluation was to assess the extent to which the PS-OC Program has been successful in reaching the goals stated below. The PS-OC Program is the only program or initiative at NCI dedicated exclusively to building trans-disciplinary teams and infrastructure to better understand and control cancer through the convergence of physical sciences and cancer biology.

Determining whether and how PS-OC funding builds infrastructure and sustains trans-disciplinary science at awarded institutions will aid program officers in identifying and maintaining the most successful components of the program while adjusting or removing other components which are not effective. The following outputs from the logic model gave direction to the evaluative process:

New Collaborations Developed

- Researchers collaborate beyond participation in PS-OCs
- Network-level collaborations form
- New multidisciplinary research groups/centers formed at participating institutions

Trainees Continue

- Undergraduate students enter field
- Cadre of graduated students, post-docs continue in field

- Development of new cross-discipline programs/certificates in physics of cancer biology

Fundamental Shifts/New Paradigms

- New paradigms established for understanding cancer biology
- Discovery of fundamental laws and principles that govern cancer and its behavior
- Applied research based on findings funded by others (NCI, industry)

"Normal" Research Disseminated

- High-impact scientific publications/presentations at cancer biology conferences
- New approaches or techniques (including computational models) developed
- New approaches/techniques disseminated outside of PS-OCs

Enhanced Attention to Research Area

- Other funders pursue approaches delineated by PS-OC Program (e.g. the creation of a standing study section)
- New entry into field by researchers not participating in program
- Seminars/workshops expand, leading to creation of new sub-discipline around topic (e.g. new journal/conferences)

3. Methodology - Data Collection

DISCOVERY LOGIC

A contract was created between the OPSO and Discovery Logic to support both the mission of the PS-OC Program and OPSO through the maintenance, update, and storage of a system, database and userface, from information provided in the semi-annual progress report to bolster an ongoing process and outcomes evaluation of the program.

Discovery Logic, a Thomson Reuters Company, helps organizations understand and profit from unified scientific and business data. Its software and database solutions and analytics transform data into knowledge for critical decisions on outcomes relating to people, organizations, and ideas. At Discovery Logic's core is ScienceWire, a data services infrastructure that supports search, data mining, and data fusion and manipulation across multiple data sets.

Discovery Logic was tasked with the first phase of using the existing progress report fields to create a database and user interface that was subsequently called the Interdisciplinary Team Reporting, Analysis, and Query Resource (iTRAQR). It also included manually entering data from the PS-OC progress reports, making recommendations for adding fields, and updating the design of the user interface for external users. In addition, OPSO was interested in creating an interactive analysis tool that supports regular PS-OC Program impact analysis and evaluation, with a particular focus on measuring the convergence of physical sciences and oncology research.

3.1 Database and User Interface

3.1.1 iTRAQR

iTRAQR was created out of the need of the NCI to analyze research output among twelve PS-OCs. Research progress, outputs, and collaborative activities are monitored on an ongoing basis through comprehensive semi-annual progress reports filed by each institutional member of the PS-OC consortium. These reports are received in paper format, leaving few options to search the data, let alone analyze it. The mission of iTRAQR is twofold: First, to provide a means of entering and organizing progress report data, and second, to facilitate convenient and flexible querying, exporting, and visualization of data. The results of such analysis can be used to measure the extent to which the research output of the investigators and centers furthers the aims of the PS-OC Program as a whole (Figure 3.1).

There are several significant challenges in the development of such a system. First, to create a meaningful data model for storage of such information, one must understand the implicit structure of the progress reports. Second, data points will be represented multiple times within and between progress reports and centers, requiring data deduplication and disambiguation. For example, a project investigator named in a June progress report will frequently be named again in the December progress report. Since one of the major aims of the PS-OC Program is trans-network collaboration, this investigator may also be named in the progress reports of other centers. Such duplication greatly increases the complexity of data analysis.

Other efforts to analyze and catalog research output and collaborations have been made at an institutional level and beyond. The VIVO web application developed by Cornell University supports discovery of cross-disciplinary research using data entered at the individual researcher level. Harvard Catalyst Profiles allows researchers to use their own profiles to create “active” research networks with specific colleagues, while “passive” networks are automatically created using such information as co-authorship history and institutional affiliation. iTRAQR differs from these institutional-based systems in that it was created for a funding organization to collect and analyze and evaluate project-based research outputs.

3.1.2 Data Model

The foundation for the entire iTRAQR system is a robust data model that conforms to the explicit and implicit structure of the PS-OC semi-annual reports and extended scientific reports (ESR) submitted to PS-OC. The report template breaks down reported information by sections and projects, but implicit in the data are many more relationships than can be inferred from a report template. An entity-relationship diagram was created to express these relationships.

A key to this approach is to take categories of information that may be repeated and consider them entities in the data model. For example, a person reported in a progress report could exist in several different relationships. This person could serve in one or more roles, such as principal investigator (PI) of the center, co-investigator on one or more research projects, collaborator in a trans-network collaboration, or co-author on a publication, to name only a few. Similarly, a publication could be associated with both a pilot project and an explicitly reported collaboration.

Following this method the complexity of such a model can grow quickly. Thus, the initial data model was created only to capture the relationships implicit in a single progress report. This is sufficient to individually analyze report contents, but the best and most comprehensive understanding of the progress of the PS-OC Program would come from cross-center and time-series analyses that would be very difficult simply treating progress reports individually.

3.1.3 Data Deduplication

The duplication of progress report data across centers and over time presented one of the greatest challenges in the development of iTRAQR, but also one of the greatest opportunities to provide meaningful understanding of the data. Many categories of data required deduplication, including people, collaborations, publications, meetings, and others.

It was crucial that in deduplicating progress report data that the integrity of individually entered progress reports was maintained. That is, it was important that a record remained of data as it was reported in a given progress report. For this reason, progress report entities were left unchanged, but were instead linked to one another across centers and time.

3.1.4 Data Entry User Interface

With the data model established, the next challenge was to provide a comprehensive and efficient means to enter data into the database. A web application was ideally suited for this purpose. Leveraging Microsoft's Entity Framework object/relational mapping system, the data model was adapted to serve as the model in a Model-View-Controller (MVC) application. A Microsoft SQL Server database was created based on this model.

The user interface made considerable use of Asynchronous JavaScript and XML (AJAX) to provide a responsive, interactive environment for data entry. AJAX modal dialog boxes served as a primary means for entering structured data.

Within a progress report, each element (such as a person) only had to be entered once and then linked in to other roles in the report as data entry proceeded. The UI was structured in a similar format to a paper ESR to streamline the data entry progress. Entities could be linked to either current data within an existing progress report or to previously reported data. The new data reported in the current progress report is entered in addition to these links, preserving the integrity of individual reports.

A quality assurance process was established whereby individual report sections could be marked as completed, then after careful checking, marked as verified. Only data marked as verified were made available to the analysis functions of iTRAQR.

3.1.5 Analysis User Interface

The purpose of iTRAQR's analysis system is to leverage all previous Data Model and Data Entry UI work to support ongoing program evaluation. The Analysis UI consists of two major parts. First, the Report Cards and Export subsystem provides textual data about the progress reports. Second, the Visualization subsystem allows data to be viewed in numerous ways, ranging from bar, pie, and line

charts to network diagrams showing center and investigator collaborations. Search functionality is also included to permit easy access to raw progress report data and to link to summary pages.

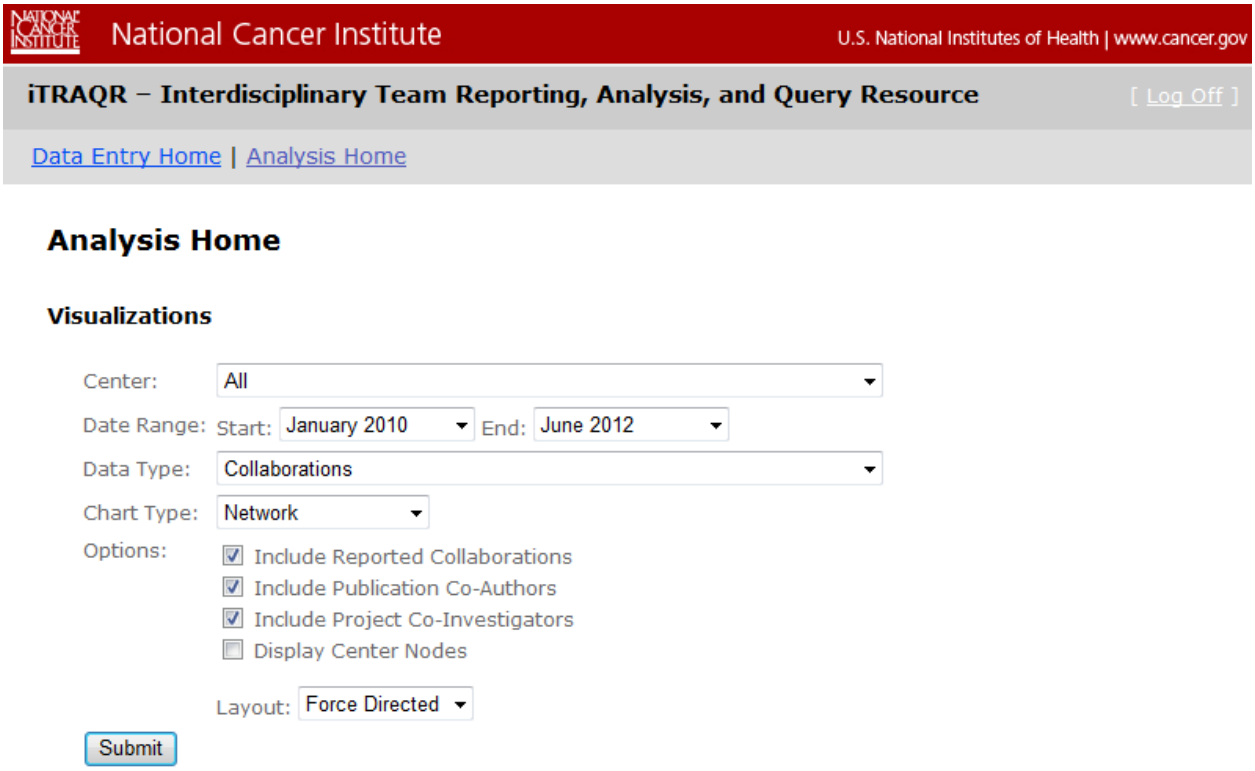

Figure 3.1. Analysis User Interface in iTRAQR. Filters allow the user to easily customize and select a specific chart or graph.

"Report cards" are an element of the iTRAQR Analysis System providing summary data at a network, center, reporting period, project, or investigator level. This facilitates viewing, for example, how many unique publications an investigator has published, or how many unique trainees a center has trained. It is then possible to export this data to a spreadsheet.

The visualization section allows the user to flexibly request many types of charts and graphs. It relies on queries very similar to those used in the Report Cards and Export section. Filters can be applied by center and reporting period. In particular, iTRAQR's network visualizations allow the user to see many types of collaborations at a glance (Figure 3.2A).

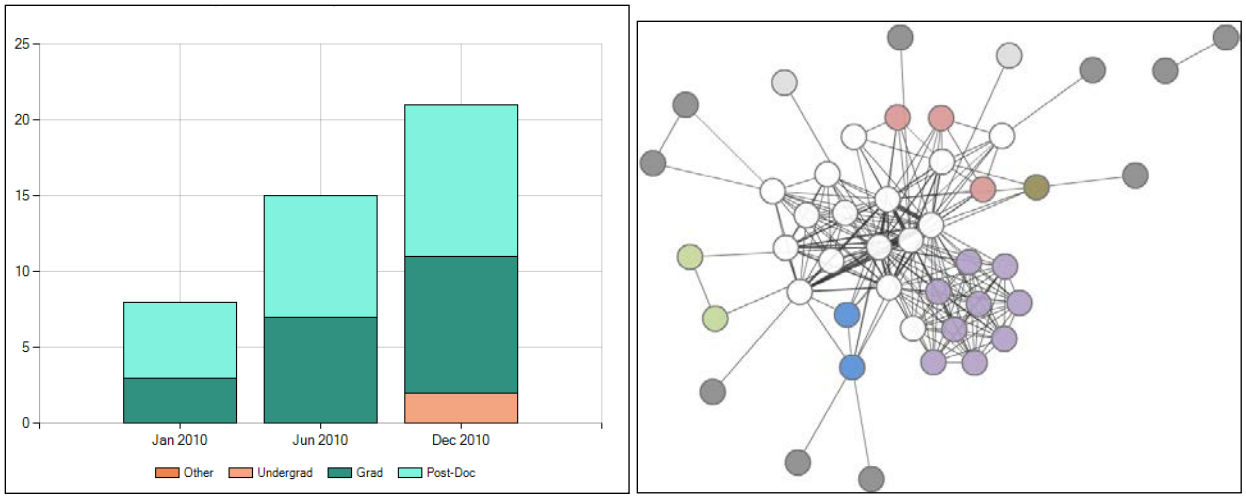

Figure 3.2*:* Graphical output of iTRAQR analysis user interface. (A) A bar chart generated in iTRAQR showing students trained over several reporting periods (B) A network diagram generated in iTRAQR showing researcher collaborations over time within a center (researcher names removed). Colors represent research projects

To show investigator collaborations, iTRAQR generates a network graph. The nodes represent PS-OC investigators that have been involved in a reported collaboration, co-authored a publication, or have been reported as a co-investigator on a project, and the edges represent the number of collaborations between investigators (Figure 3.2B).

To create these graphs, queries must be made on the database for unique investigators, collaborations, publications, and projects. The system aggregates this information into a custom data structure. This data structure is used to generate a GraphML file consisting of nodes, edges, and associated colors to represent the investigators, the project(s) they belong to, and the number of collaborations between each pair of investigators.

Leveraging the Cytoscape Web visualization component, the generated GraphML file is rendered visually on the page. This visualization is highly customizable, supporting user interaction with nodes and edges, image export, and other functions. From this page, the user can also export a spreadsheet containing such measures such as density, degree, closeness centrality, and betweenness centrality.

3.2 Independent Data Collection and Analysis

In addition to the data explicitly stated in the progress report, PS-OC Program staff were interested in collecting and analyzing outputs using other data sources and databases. OSPO instructed Discovery Logic to conduct an independent collection and data analysis of program metrics and indicators listed below. Using MEDLINE and Web of Science databases, Discovery Logic was able to derive publication sets of key PS-OC investigators (PIs, SIs, and Project leaders) from 2004 to June 2012, using name matching algorithms augmented by author metadata including email address. These publication sets were used to analyze metrics before and after the PS-OC Program to compare the impact of the Program on

investigator scientific output and collaborations. The results of these comparisons are described in the following sections.

Bibliometric Analysis on PS-OC Network Publications – Discovery Logic collected and analyzed information on PS-OC investigator publications before and after the PS-OC Program. The following metrics were analyzed.

- Journal Impact Factor
- Citations
- Expected Citations: Compare the current performance of a publication with other similar publications using expected citations.
- Bibliometric Percentiles: A publication percentile is determined by obtaining the set of publications in the same year and Web of Science Journal Subject Category as the publication of interest[1].
- Breakthrough Publications: Discovery Logic employed an algorithm to detect breakthrough publications to explore early the innovative research with a potential for substantial impact.

Analysis of Authorship Collaborations – Using PS-OC investigator disciplines that were self-identified, Discovery Logic determined the number and types (trans-disciplinary or intra-disciplinary) of authorship collaborations between investigators in the PS-OC Network.

Field Convergence of Physical Sciences and Oncology – Discover Logic established a list of terms to categorize PS-OC investigator publications into disciplines and identified trans-disciplinary publications that have resulted from the collaborative knowledge and techniques of PS-OC Network Physical Scientists and Oncologists.

4. Program Analyses

4.1 Bibliometric Analysis on PS-OC Network Publications

4.1.1 Journal Impact Factor

The journal impact factor metric is a measure of the citation frequency expected for an average article in a specified period of time for a specific journal. It is typically used as a measure a journal's prestige and thus also serves as an indirect measure of an article's scientific merit. As it is a widely used metric, the average journal impact factor for the program was calculated by Discovery Logic. The average for all 12 PS-OC was 9.82.

Table 4.1: Average journal impact factor of the PS-OC Network publications by Center.

Center	Impact Factor	Number of Publications
ASU	9.10	24
Berkeley	10.83	42

[1] Thomson Reuters, Scientific. Whitepaper Using Bibliometrics: A Guide to Evaluating Research Performance with Citation Data.

Cornell	8.97	46
DFCI	11.97	130
JHU	8.75	66
Methodist	8.56	36
MIT	18.44	23
Moffitt	6.59	70
Northwestern	9.83	67
Princeton	9.11	20
Scripps	5.00	18
USC	10.65	71
Average	**9.82**	**51.08**

4.1.2 CITATIONS

Another measure of the quality of PS-OC publications is the number of times they have been cited by other researchers. Table 4.2 presents the number of times that the 613 papers for which bibliometric data are available have been cited. Seven papers (1.1%) have been cited more than 50 times in less than three years, and an additional 44 (7%) have been cited between 20 and 50 times. These 8% of papers represent two-thirds of the citations on publications in the PS-OC Network.

Table 4.2: Citations to PS-OC Publications

Citations per paper	Papers with # of citations	Percentage of papers	Number of citations	Percentage of citations
101+	7	1.2%	1079	22.0%
51 to 100	14	2.4%	892	18.2%
21 to 51	44	7.7%	1378	28.1%
1 to 20	272	47.6%	1549	31.6%
0	56	9.8%	0	0.0%

4.1.3 EXPECTED CITATIONS

Journal impact factor is intended as a measure of the "quality" of the journals in which a paper is published, while the number of citations is normally interpreted as a measure of how useful the paper has been to the research community. Expected number of citations to a publication is a measure that aims to combine the two, normalizing the number of citations to an individual paper against others in the same journal and issue to determine whether the paper has been cited more often than expected. Actual citations were compared to expected citations for the papers published 2009- July 2011 (353

publications); papers published after June 2012 were excluded because there was not enough data available on citations and reference publications. The mean actual-to-expected ratio was 1.8, suggesting that PS-OC-supported publications are 1.8 times more highly-cited as others in their peer cohorts. Over 9% of PS-OC publications had a citation rate 5 times higher than expected (Table 4.3). To be most meaningful, it is also important to have a direct comparison of this metric using PS-OC investigators' publication history as a background. For all of the Centers, the average expected citation ratio for their publication increased during the grant years versus the five years prior to the PS-OC Program.

Table 4.3: Citation Benchmarks of PS-OC Publications (Ratio of actual to expected citations)

Ratio (Actual to Expected Citations)	Papers with ratio	Percentage of publications
5+	32	9.1%
4.1 - 5.0	10	2.8%
3.1 - 4.0	22	6.2%
2.1 - 3.0	30	8.5%
1.1- 2.0	88	24.9%
0.1-1.0	107	30.3%
0	64	18.1%

Source: Publications published prior to July 2011. 353 publications total.

4.1.4 Bibliometric Percentile

To measure impact of the PS-OC Program on scientific performance of PS-OC investigators an analysis was performed comparing the bibliometrics (average impact factor, first year citations, and citation benchmark) before and after the start of the PS-OC Program (September 2009). The results indicate an increase in investigator output during the PS-OC Program. Average journal impact factor for PS-OC investigators increased from 7.3 to 9.8 (Figure 4.1). A increase in impact factor indicates that PS-OC investigators are publishing in higher impact journals during their involvement in the PS-OC Program compared to pre-PS-OCs. This increase is largely due to physical scientists publishing in more medically affiliated journals that on average have a higher impact factor than physical science journals. Two other metrics increased slightly. The average first year citation rate of publications increased slightly (5.8 to 6.6 citations in 1 year) and the citation benchmark value increased from (1.91 to 1.98). This all suggest that the PS-OC Program is contributing to increased scientific output of its investigators.

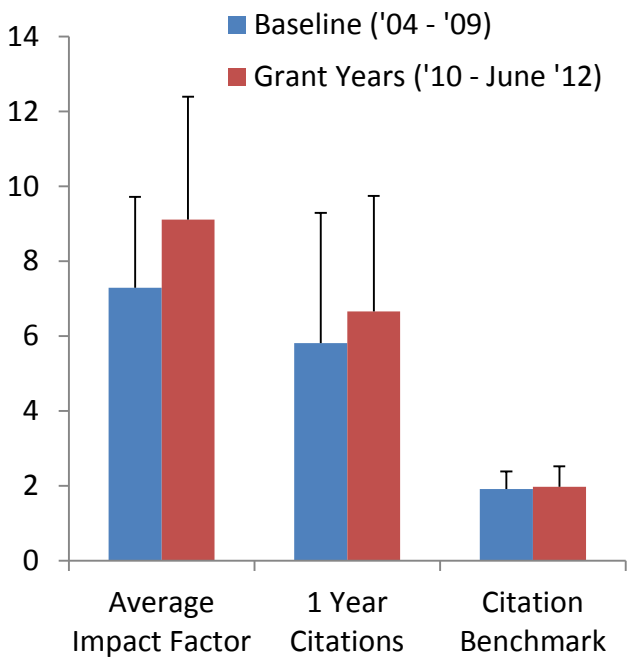

Figure 4.1. Comparison of PS-OC investigator publications before and after the start of the PS-OC Program. Average journal impact factor, 1 year citations, and citation benchmark of investigator publications was calculated before (Baseline – 2004-2009, Blue) and after (Grant Years – 2010 to June 2012, Red) the start of the PS-OC Program.

4.1.5 BREAKTHROUGH PUBLICATIONS

It typically takes five years of data to identify a breakthrough publication due to the length of time it takes to accumulate a substantial number of citations relative to similar publications in that journal category. Because the PS-OC Program is only three years old, other methods were explored for identifying breakthrough science. Thomson Reuters has developed an algorithm to detect breakthrough publications earlier using citation velocity after 6, 12, or 24 months. This algorithm was applied to PS-OC papers published prior to July 2011 to identify potential breakthrough PS-OC scientific results. The algorithm uses a non-linear projection of the paper's citation velocity to predict the five year citation level of a publication and compares that directly with a citation threshold of known breakthrough publications in a given subject area. If the level of citations is predicted to exceed the threshold then it is listed as a potential breakthrough publication.

Using this methodology, the PS-OC Program has 18 potential breakthrough publications identified from Jan-2010 through July-2011. Nine out of twelve PS-OC have published a potential breakthrough publication (Table 4.4). DFCI and JHU PS-OCs have the highest number of potential breakthrough publications, 4. They are followed by ASU PS-OC, Moffitt PS-OC, USC PS-OC, and Cornell PS-OC each with 2 potential breakthrough publications. A breakdown of the number of breakthrough publications by year and Center are listed below.

Table 4.4. Breakthrough Publications

	Year Published	
PS-OC Name	2010	2011
ASU	2	0
Berkeley	0	0
Cornell	2	0
DFCI	3	1
JHU	3	1
Methodist	1	0
MIT	1	1
Moffitt	1	1
Northwestern	1	0
Princeton	0	0
Scripps	0	0
USC	1	1

4.2 Authorship Collaborations

Discovery logic has categorized the co-author collaborations of investigators in the PS-OC Program before and after the initiation of the program (pre and post september 2009). The collaborations were categorized by the disciplines of investigators in each collaboration, oncology-onoclogy, physical sciences - physical sciences, and oncology -physical sciences. Investigator publication sets were derived from MEDLINE and Web of Science using name matching algorithms augmented by author metadata including email address. Publications were identified with a high degree of accuracy that was determined by a precision/recall analysis. Author discipline was determined using program information. Each publication author list was analyzed to determine affiliation(s)

4.2.1 Expected Citations

Journal impact factor is intended as a measure of the "quality" of the journals in which a paper is published, while the number of citations is normally interpreted as a measure of how useful the paper has been to the research community. Expected number of citations to a publication is a measure that aims to combine the two, normalizing the number of citations to an individual paper against others in the same

journal and issue to determine whether the paper has been cited more often than expected. Expected citations allow for a direct comparison of the publication to others in similar fields. It is valuable for programs, such as the PS-OC program, that have a variety of different fields within the program. To be most meaningful, it is also important to have a direct comparison of this metric using PS-OC investigators' publication history as a background. Actual citations were compared to expected citations for the papers published between October 2009- July 2011 (353 publications); papers published after June 2012 were excluded because there was not enough data available on citations and reference publications. The mean actual-to-expected ratio was 1.8, suggesting that PS-OC-supported publications are 1.8 times more highly-cited as others in their peer cohorts. Over 9% of PS-OC publications had a citation rate 5 times higher than expected (Table 4.3). For all of the Centers, the average expected citation ratio for their publication increased during the grant years versus the five years prior to the PS-OC Program.

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4.2.2 BIBLIOMETRIC PERCENTILE

To measure impact of the PS-OC Program on scientific performance of PS-OC investigators an analysis was performed comparing the bibliometrics (average impact factor, first year citations, and citation benchmark) before and after the start of the PS-OC Program (September 2009). The results indicate an increase in investigator output during the PS-OC Program. Average journal impact factor for PS-OC investigators increased from 7.3 to 9.8 (Figure 4.1). A increase in impact factor indicates that PS-OC investigators are publishing in higher impact journals during their involvement in the PS-OC Program compared to pre-PS-OCs. This increase is largely due to physical scientists publishing in more medically

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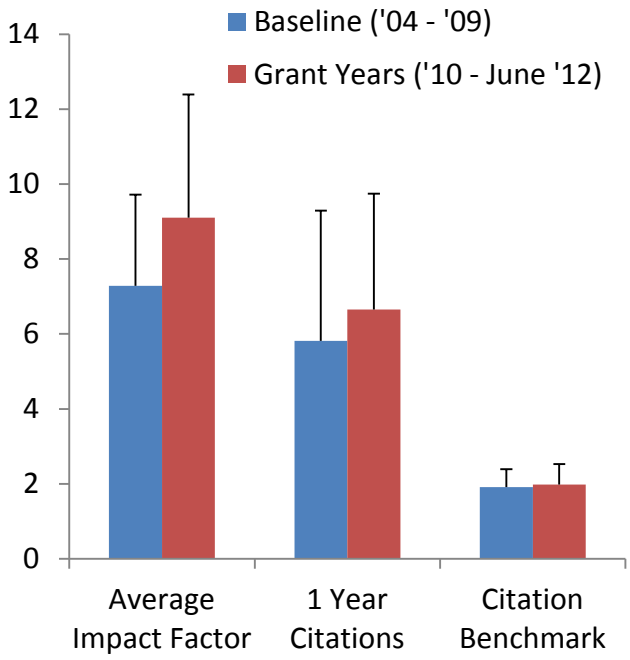

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MIT	1	1
Moffitt	1	1
Northwestern	1	0
Princeton	0	0
Scripps	0	0
USC	1	1

4.3 Authorship Collaborations

Discovery Logic has categorized the co-author collaborations of investigators in the PS-OC Program before and after the initiation of the program (pre and post September 2009). The collaborations were categorized by the disciplines of investigators in each collaboration, oncology-onoclogy, physical sciences - physical sciences, and oncology -physical sciences. Investigator publication sets were derived from MEDLINE and Web of Science using name matching algorithms augmented by author metadata including email address. Publications were identified with a high degree of accuracy that was determined by a precision/recall analysis. Author discipline was determined using program information. Each publication author list was analyzed to determine affiliation(s) with the PS-OC Program and research discipline (physical science or oncology).

Circular network graphs were created in Gephi2 to examine within and between discipline co-author collaborations between PS-OC investigators before (2004-2008) and after (October 2009-June 2012) the program was initiated. Each network graph node represented a PS-OC investigator and edges connected co-authors. The weight of the edge represented co-author occurrence. Nodes were colored according to discipline; oncologists were red and physical scientists blue. Edges were colored according to the type of collaboration. A collaboration between oncologists was colored red, between physical scientists colored blue and a collaboration between an oncologist and physical scientists was colored green. The percentage of trans-disciplinary collaborations has increased 8% since the start of the PS-OC Program (Figure 5.4).

4.4 Field Convergence

The PS-OC Program emphasizes convergence of physical sciences and oncology fields through team science to support new and innovative approaches and theories in cancer research. Indicators of collaborations were collected via progress reports and surveys to reflect the increase in connectivity between investigators. However, measuring the impact of the PS-OC Program on convergence of two disparate fields to form a new Physical Sciences in Oncology field is a unique challenge that became a focus of the PS-OC Program officials to monitor program performance. The PS-OC Programofficials worked with Discovery Logic to design a novel indicator for monitoring convergence of these fields based on scientific output.

The Web of Science (WOS) database identifies each journal with a scientific category. Using this classification, several journals were identified as containing physical sciences or oncology publications. 100,000 publications were randomly selected from each of these categories of journals. All titles and abstracts from these 200,000 publications were mined for words, removing common English words, and stemming words. This resulted in over 65,000 single word terms identified for each category, physical sciences or oncology. Additional criteria were imposed on these lists of terms to identify unique and relevant terms for each category, which include the following:

Criteria for physical science terms:

- Must occur in greater than 70% of physical sciences publications and less than 30% of biology or oncology publications
- Identified as a strong descriptive single word term by manual selection

Criteria for oncology terms:

- Must occur in greater than 90% of oncology publications
- Must be part of a MESH term

The final list of unique terms included 1643 physical sciences terms and 571 oncology terms. Each PS-OC investigator publication was classified into a type of publication based on these terms. If the publication contains only physical sciences terms it was be considered a physical sciences publications. If publication contains only oncology terms it was considered to be an oncology publication. If the

publication contained terms from both categories it was considered to be a physical sciences in oncology publication. If the publication did not contain any of these terms it was put in the “other” category.

PS-OC investigators publications were identified from five years prior to the PS-OC Program to use as a baseline for monitoring convergence of these fields in the output of PS-OC investigators' publications.

To date, the PS-OC Program has observed a 20% increase in the percentage of PS-OC investigator's publications that converge the physical sciences and oncology fields. Currently, 40% of all investigators publications contain terms from both physical sciences and oncology (Figure 4.2). It was observed that the percentage of oncology specific publications has remained constant with the start of the PS-OC Program, but the percentage of pure physical sciences publications has decreased. If the results are broken down by investigator discipline, it was observed that the increase in convergence is due to physical scientists publishing more oncology relevant publications. Cancer researchers have a slight increase in the amount of physical science publications since the grant was started in 2009.

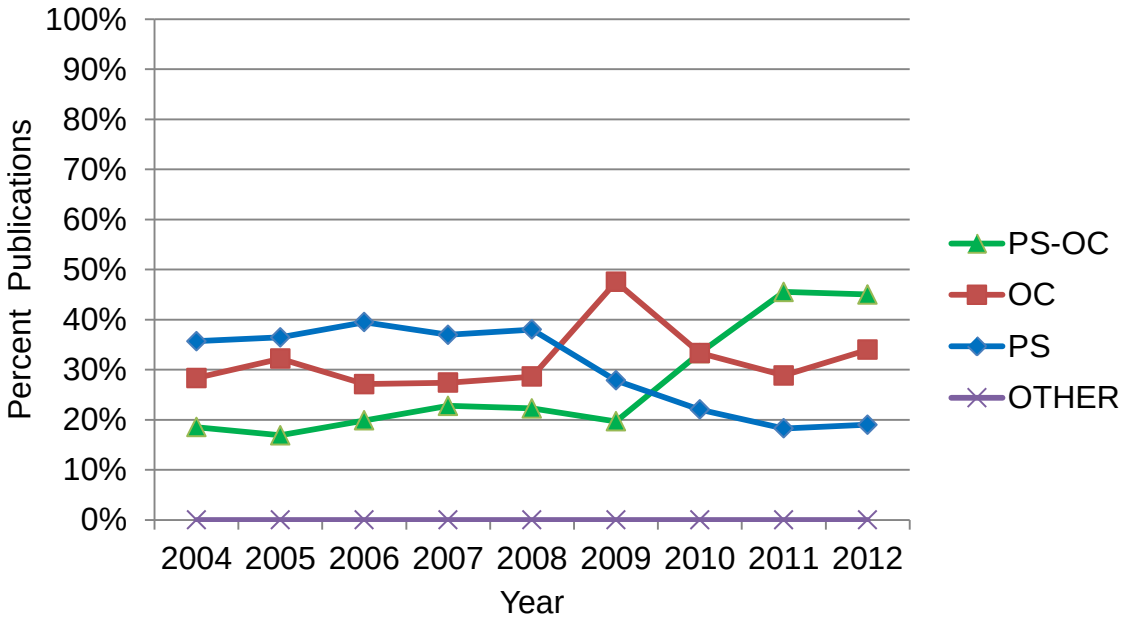

Figure 4.2: Classification of PS-OC Investigator publications by discipline from 2004 to present. Unique terms were used to classify publications before and after PS-OC funding. The percentage of publications with both physical sciences and oncology terms has increased from below 20% to over 40% of all publications since the program was initiated in 2009. PS-OC (green) is the percentage of publications identified in the oncology and physical sciences, OC (red) is the percentage of oncology publicaitons, PS (blue) is the percentage of publications in the physical sciences category, and other (purple) is the percentage of publications that could not be classified.

A breakdown look at each Center displays the range of convergence across the PS-OC Network. All PS-OC have increased the percentage of trans-disciplinary publications as a result of the PS-OC Program

support. The range of increase in trans-disciplinary publications from pre-grant years to post-grant years ranges between 5% and 40% depending on the PS-OC (Figure 4.3).

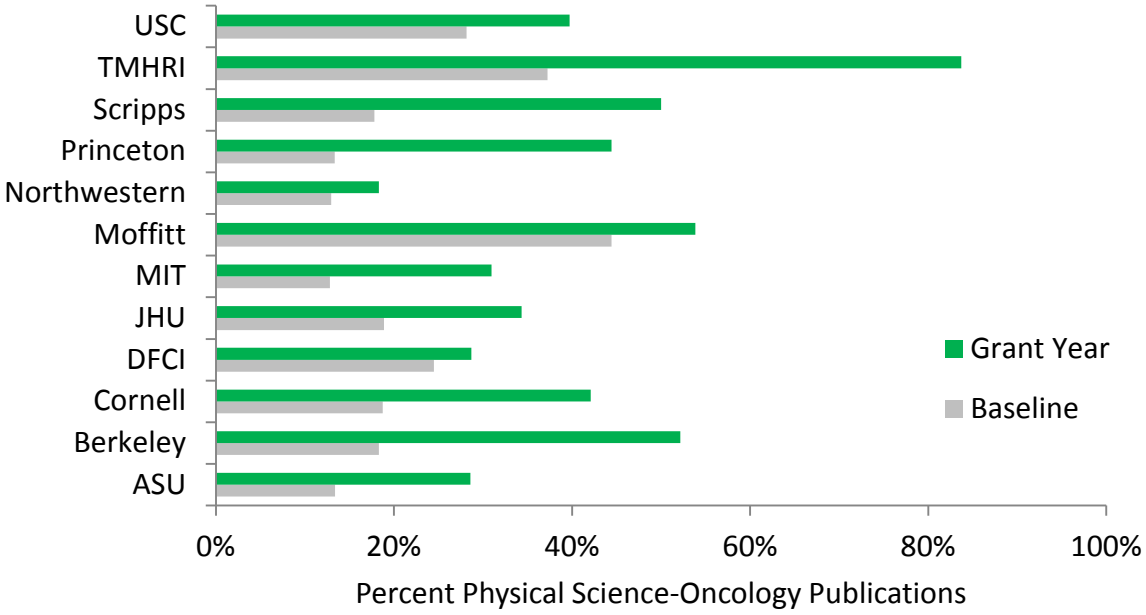

Figure 4.3: The breakdown of publication category by PS-OC before and after PS-OC funding. The percentage of trans-disciplinary publications increased during the grant years.

Program staff anticipates the percentage of trans-disciplinary publications to grow as collaborations mature. In addition, it is expected that more physical scientists will continue to expand their knowledge and publish more in the oncology fields. The impact of the PS-OC Program on the types of publications these investigators is producing appears to be substantial and it is anticipated that impact will grow over time (Figure 4.4).

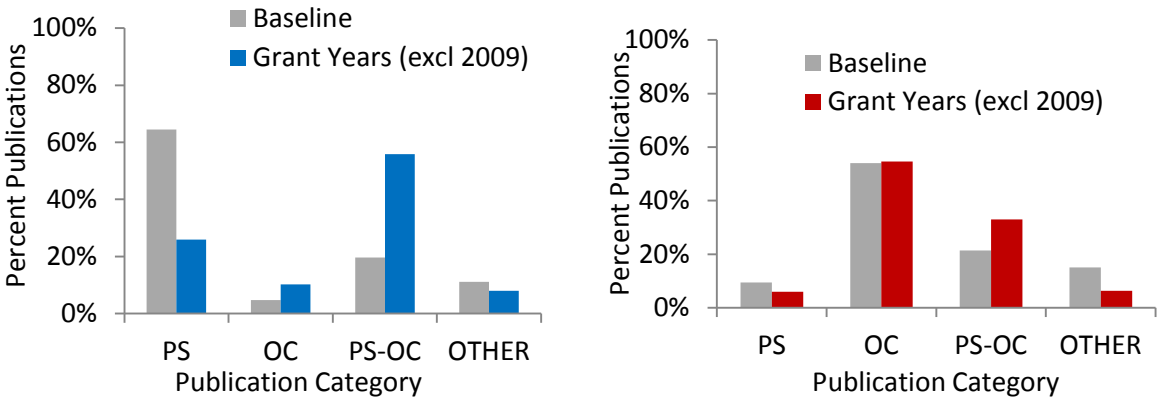

Figure 4.4.: The breakdown of publication types based on investigator discipline (A) The breakdown of physical scientists publications by category (physical sciences (PS), oncology (OC), physical sciences – oncology (PS-OC), and other) (B) (A) The breakdown of oncologists/cancer biologists publications by category (physical sciences (PS), oncology (OC), physical sciences – oncology (PS-OC), and other). For these figures the base line is 2004-2008 and the grant years is 2010-June 2012. Any months in 2009 during the grant were exclude completely from the grant years category (excl 2009).

5. Evaluation Findings

5.1 Research Disseminated through Publications

The information from the progress reports has been quantified to reveal the overall progression of the PS-OC Network to date. The progress reports provided details on the number and types of publications that each center produced. A list of PS-OC publications was compiled from programmatic records and searches of MEDLINE-indexed peer reviewed journals in which authors acknowledge PS-OC funding.

Using these methods, a total of 613 publications, 572 peer-reviewed publications, were attributed to the PS-OC Program, of which 10 are associated with more than one PS-OC (i.e. trans-Network). The other 41 publications , not peer-reviewed, include comments, news articles, and conference proceedings. Analysis of publication numbers and trends reveals several interesting observations. First, the number of publications per PS-OC varied substantially, with DFCI exceeding 100 publications, USC, Moffitt, JHU, and Northwestern publishing between 50 and 75 papers, and ASU, UCB, Cornell, TMHRI, Princeton, and Scripps between 18 and 46 (Table 5.1). The average number of publications per year also varied across PS-OCs. As expected, the number of publications has increased each year for most PS-OCs, with an average of over 200 publications per funding year. It took approximately 1.5 years for the PS-OC Program to reach its current level of publishing. PS-OC Program officials attribute a slower publication rate for the first 1.5 years to establishing the infrastructure of the PS-OC, initial communication barriers between scientists, and formation of new collaborations based on discussions with PS-OC investigators.

Table 5.1 Breakdown of PS-OC Publications by year and Center.

CENTER	2009 (Sept - Dec)	2010	2011	2012 (Jan -June)	Average Publications Per Year of Funding
ASU	5	6	11	2	8.0
UCB	0	12	25	5	14.0
Cornell	2	12	21	11	15.3

DFCI	16	40	52	22	43.3
JHU	11	25	17	13	22.0
TMHRI	2	17	11	6	12.0
MIT	3	3	10	7	7.7
Moffitt	4	22	26	18	23.3
Northwestern	9	23	27	8	22.3
Princeton	3	6	10	1	6.7
Scripps	0	5	5	8	6.0
USC	7	22	29	13	23.7
Total	**62**	**193**	**244**	**114**	**204.3**

Taken together, the total number of publications per year associated with the PS-OC Program and has increased over time, while total programmatic funding has remained roughly constant since FY 2009 (Figure 5.1). The ratio of dollars per publication has decreased significantly in the first three years of the program, with less than $100k per publication in 2012.

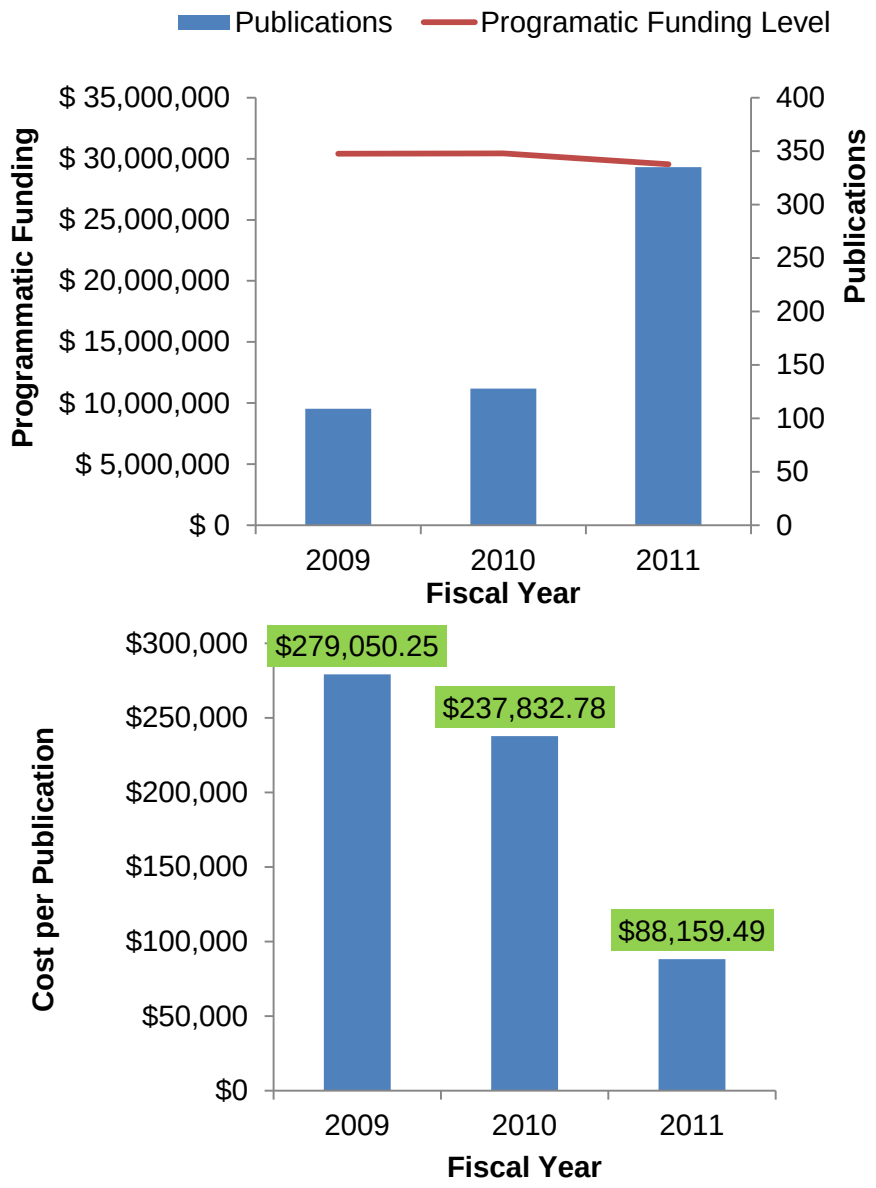

Figure 5.1: Ratio of Programmatic Funding to Number of Publications, 2009-Present. (A) The number of publications per grant year based on the fiscal year of funding. (B) The cost per publication by grant year based on the fiscal year of funding..

5.1.1 PUBLICATION QUALITY

A list of PS-OC publications identified from the progress reports was submitted to Discovery Logic for bibliometric analysis, and data on 613 publications were matched to their database, of which 572

publications are peer-reviewed articles. The following analyses are based on the bibliometric data acquired on these publications as of June 2012.

PS-OC research was published in 178 distinct journals spanning a range of fields, including cancer biology, computational biology, clinical oncology, and biophysics. Two journals, *PLOS ONE* and *Proceedings of the National Academy of Sciences (PNAS)*, accounted for 11% of all PS-OC publications. These two journals are diverse in the type of science that they publish and appear to be receptive to the trans-disciplinary research from the PS-OC Network. Following these two journals, there is a broad mix of journals. A list of the top 12 journals where PS-OC research was published is in Table 4.2. A total of 12 journals (7% of the 178 total) accounted for 27% of the total papers (167 of 613 papers); impact factors of those journals ranged between 4 and 36 (Table 4.2). The journals in which the largest number of articles appears include interdisciplinary journals (*PLOS One, PNAS, Nature, PLOS Computational Biology, Blood), oncology journals (Cancer Research, Clinical Cancer Research, Cancer Cell),* and physical science journals (*Biophysical Journal, Physics Review Letters, Nano Letters*).

Table 4.2: Journals with Largest Number of Articles Thomson/ISI Indexed

Journal	Number of Publications	Journal Impact Factor
PLOS ONE	39	4.411
PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	33	9.771
CANCER RESEARCH	15	8.234
BLOOD	14	10.558
NATURE	12	36.101
PLOS COMPUATIONAL BIOLOGY	10	5.759
CLINICAL CANCER RESEARCH	8	7.338
BIOPHYSICAL JOURNAL	8	4.218
CANCER CELL	7	26.925
PHYSICAL REVIEW LETTERS	7	7.621
NANO LETTERS	7	12.186

CELL	7	32.401

Sixty-two PS-OC publications (10%) were in journals with impact factors of 20 or higher, including 12 in *Nature*, 5 papers in *Science*,7 in *Cell*, and one each in the *New England Journal of Medicine* (Table 4.3). Looking across all of the PS-OC publications, the average impact factor was 9.82, and the median was 9.11 per Center.

Table 4.3: PS-OC Publications in Very High-Impact-Factor Journals

Very High Impact Journals	Impact factor	Number of Publications
NEW ENGLAND JOURNAL OF MEDICINE	53.484	1
NATURE REVIEWS CANCER	37.178	5
NATURE GENETICS	36.377	5
NATURE	36.101	12
NATURE REVIEWS GENETICS	32.745	2
CELL	32.401	7
SCIENCE	31.364	5
NATURE BIOTECHNOLOGY	31.085	6
NATURE NANOTECHNOLOGY	30.306	3
CANCER CELL	26.925	7
CHEMICAL SOCIETY REVIEWS	26.583	1
CELL STEM CELL	25.943	4
NATURE METHODS	20.717	4

5.2 New Collaborations Developed

In each progress report, PS-OC investigators are asked to report on all PS-OC related collaborations they are involved in. Investigators are asked to provide information about the state of the collaboration, whether the collaboration is within the Center, within the PS-OC Network, or outside of the PS-OC Network, and provide a brief description of the collaboration. This information has been used to enumerate the total number of collaborations that have developed from the PS-OC Program. Figure 5.2 shows the cumulative number of collaborations over each reporting period. These data have been hand annotated to remove duplicate information so that a collaboration appears in the graph only the first time it appears in a progress report. The graph illustrates an increased rate of collaboration formation starting with the fourth progress report, indicating that the PS-OC Network took about 1-1.5 years to mature to the state that collaborations could more effectively form.

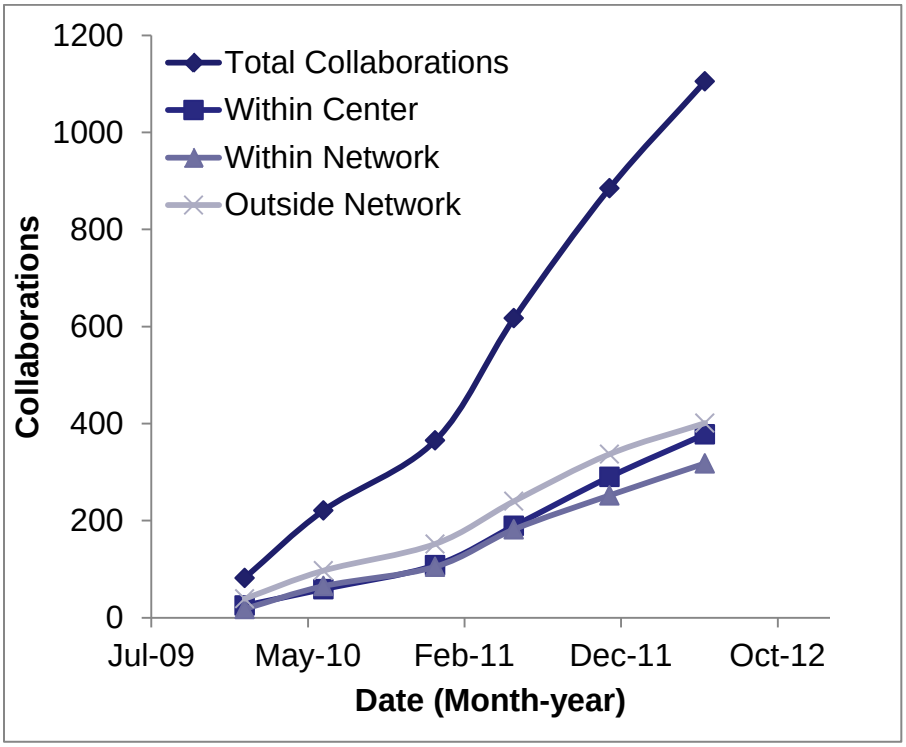

Figure 5.2 The rate of PS-OC collaboration formation increased in the second year of the program. The cumulative number of PS-OC collaborations reported in each progress report is plotted. Diamonds represent total collaborations, squares represent within Center collaborations, triangles represent within Network collaborations, Xs represent outside of Network collaborations.

The iTRAQR network analysis tool was used to investigate the collaboration and integration within individual Centers. Plotting the network interaction maps for each PS-OC reveals that the Centers are both expanding and becoming more integrated over time (Figure 5.3). Evaluation of the Center collaborations over time revealed two types of dynamics. Some Centers, including Cornell and Scripps, were initially only loosely integrated and through the first three years of the PS-OC Program these Centers have both connected and expanded (Figure 5.3a-b). Other Centers, including Moffitt, initially reported a core set of integrated investigators that has expanded overtime through initiating Center Pilot Projects, Outreach Pilot Projects, Trans-Network projects, and other collaborations (Figure 5.3c).

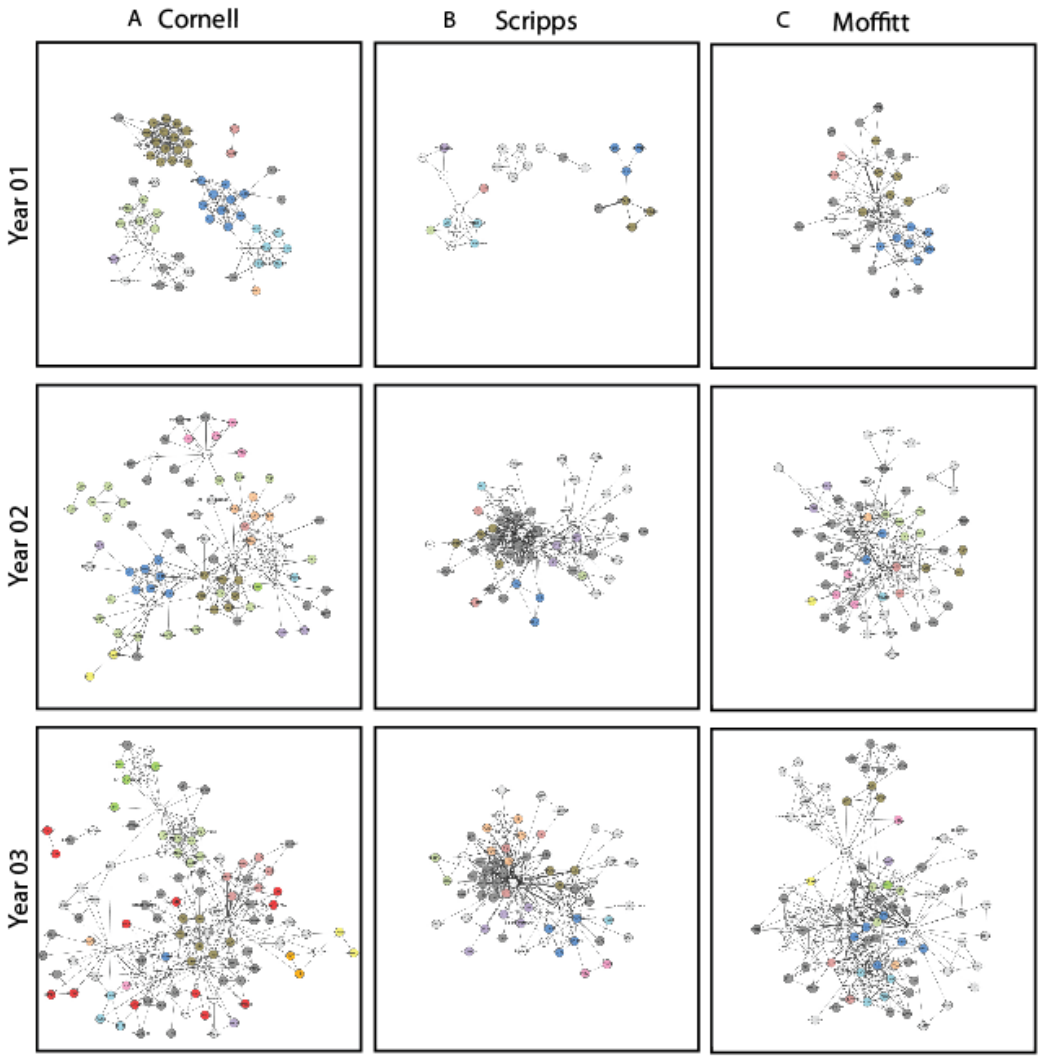

Figure 5.3. Centers expand and become more integrated over the course of the PS-OC Program. iTRAQR was used to plot the network interaction maps of the **(A)** Cornell, **(B)** Scripps, and **(C)** Moffitt PS-OCs over time. Network interaction maps represent all within Center and within the PS-OC Network collaborations. Year 01 represents January and June 2010 progress reports, Year 02 represents December 2010 and June 2011 progress reports, and Year 03 represents December 2011 and June 2012 progress reports. The color of the nodes represents the project(s) an investigator is involved in.

The iTRAQR network analysis tool was also used to examine the evolution of the PS-OC Network-wide collaboration landscape. Collaborations and integration of the Network was investigated using all collaboration types or only reported and authorship collaborations (Figure 5.4). Qualitatively, it is clear that over the first three years of the PS-OC Program that the accumulation of collaborations has resulted in a more integrated Network of investigators (Figure 5.4). When considering all PS-OC collaboration

types the PS-OC Network density, a measure of the total interactions versus all possible interactions, has more than doubled from Year 1 to Year 3. When only reported and authorship collaborations are measured, the density has increased more than four-fold over the first three years of the program. Similar trends are seen when only looking at the collaborations reported for the Center Principal Investigators (PIs) and Senior Co-Investigators (SIs). Taken together, the collaboration data illustrates that collaborative teams have become more integrated at both the Center and Network level.

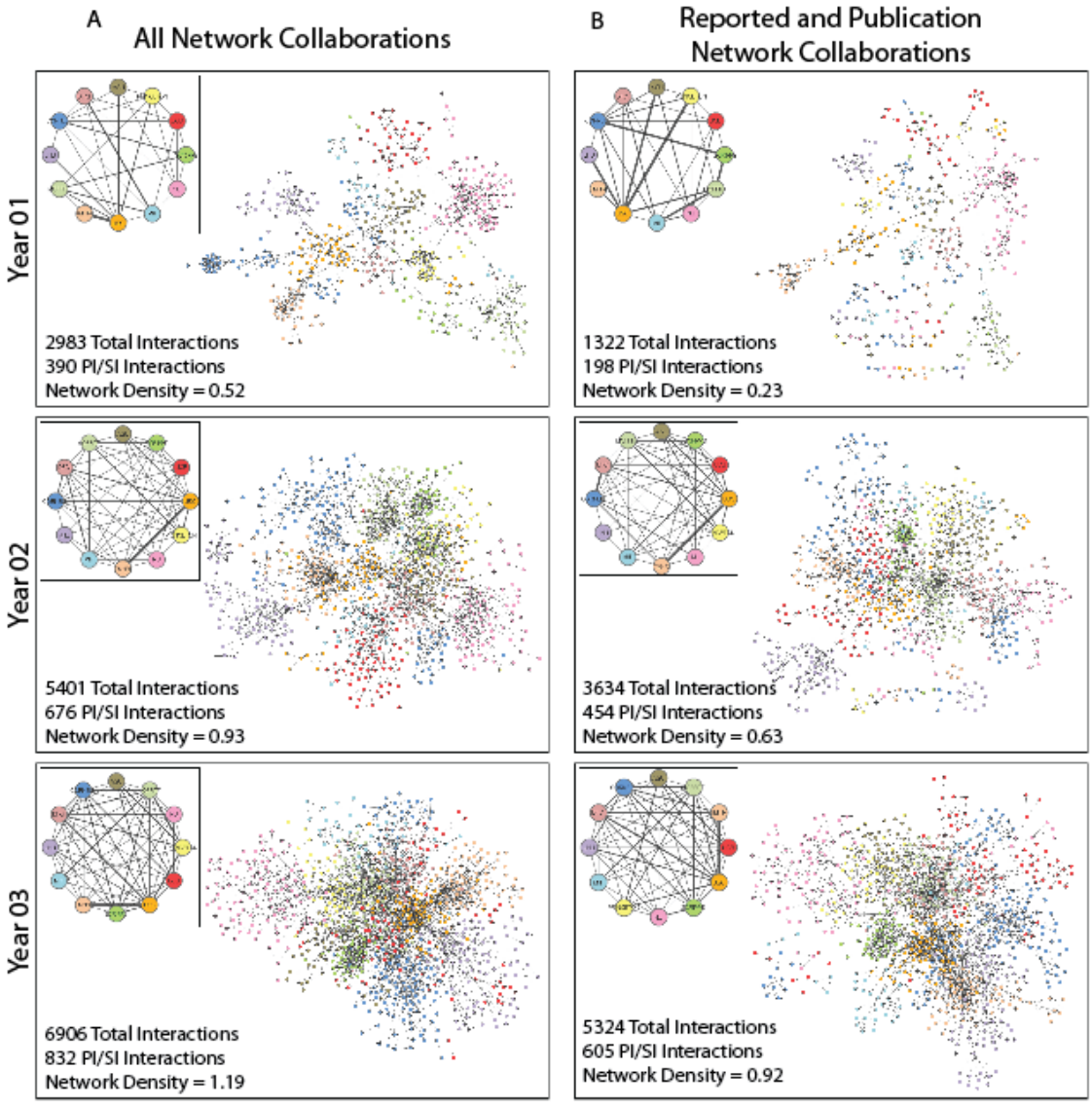

Figure 5.4: The landscape of the PS-OC Network becomes more integrated over the course of the PS-OC Program. iTRAQR was used to plot the network interaction maps based on (A) all collaboration types and (B) reported and authorship collaborations over time. Insets represent a summary of all of the interactions

on a Center level. Year 01 represents January and June 2010 progress reports, Year 02 represents December 2010 and June 2011 progress reports, and Year 03 represents December 2011 and June 2012 progress reports. Node color represents the PS-OC an investigator is associated with.

5.3 Formation of Trans-disciplinary Collaborations

To evaluate the impact of the PS-OC Program on trans-disciplinary collaborations, the collaboration history of a set of 262 key PS-OC investigators was examined for the PS-OC grant years and the three years preceding the program. The 262 investigators were categorized as either physical scientists (134) or cancer biologists/oncologists (128), and their publication histories were used to represent collaborations. Each publication was annotated to be (i) single author, with a single physical scientist or cancer biologist author, (ii) intra-disciplinary, with multiple physical scientist or cancer biologist authors, or (iii) cross-disciplinary with at least one physical scientist and one cancer biologist author. A plot depicting each of the 262 investigators and their co-authorship collaborations illustrates a striking increase in both overall collaborations and trans-disciplinary collaborations (green lines) during the PS-OC grant years (Figure 5.5). The statistics for the change in the collaboration landscape can be examined on either a publication level or on an investigator level. On a publication level there was an approximately three-fold increase (from 4.8% to 14.8%) in the percentage of intra-disciplinary publications driven mainly by an increase in the percentage of physical scientist-physical scientist collaborations (from 1.8% to 10.3%; Table 5.2). Additionally, there was a striking 10-fold increase in the percentage of cross-disciplinary publications, going from only 1.2% of baseline year publications to 12.6% of PS-OC grant year publications. At the investigator level, intra-disciplinary collaborations remained relatively flat, with approximately 25% of investigators participating in intra-disciplinary collaborations during baseline and grant years (Table 5.3). However, there was an approximately three-fold increase (from 12.6% to 34.0%) in the percentage of investigators involved in cross-disciplinary collaborations during the PS-OC grant years. Overall, this data show that the PS-OC Program has had a positive impact in promoting trans-disciplinary collaborations. Additionally, the fact that this data is based on co-authored publications provides evidence that the collaborations fostered by the PS-OC Program are productive collaborations leading to scientific advances.

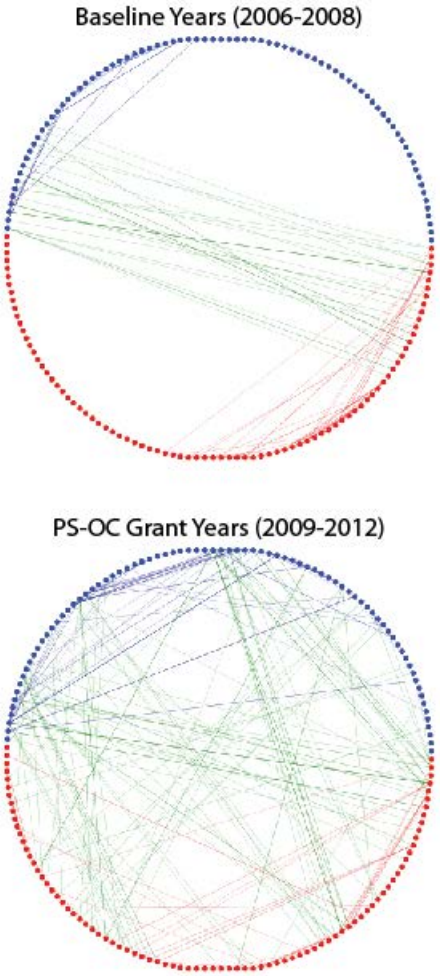

Figure 5.5: PS-OC investigators authored more cross-disciplinary publications during the PS-OC grant years than the years preceding the program. Co-authorship information was used to plot interaction between 262 key PS-OC investigators in **(A)** the three years preceding the PS-OC Program and **(B)** the first three years of the PS-OC Program. Blue dots represent physical scientists (134) and red dots represent cancer biologists/oncologists (128). Blue lines represent co-authorship collaborations between two physical scientists, red lines represent co-authorship collaborations between cancer biologists, and green lines represent cross-disciplinary co-authorship collaborations.

Table 5.2: Publication level collaborations statistics for baseline and PS-OC grant years.

	Baseline Years (2006-2008)		**Grant Years (2009-2012)**	
	N	**%**	**N**	**%**
Publications	**3093**	--	**601**	--
Single PS or OC Author	**2907**	**94.0%**	**436**	**72.5%**
1 PS author only	*1435*	*46.4%*	*232*	*38.6%*
1 OC author only	*1472*	*47.6%*	*204*	*33.9%*

Intra-disciplinary Publications*	**150**	**4.8%**	**89**	**14.8%**
PS authors only	*57*	*1.8%*	*62*	*10.3%*
OC authors only	*93*	*3.0%*	*27*	*4.5%*
Cross-disciplinary Publications*	**36**	**1.2%**	**76**	**12.6%**

* Intra-disciplinary publications include two or more in-Network investigators from the same discipline.
*Cross-disciplinary publications include at least in-Network investigator from the physical sciences and 1 from cancer biology.

Table 5.3: Investigator level collaboration statistics for baseline and PS-OC grant years.

	Baseline Years (2006-2008)		**Grant Years (2009-2012)**	
	N	%	N	%
Investigators	262	--	262	--
Intra-disciplinary Co-Authors*	67	25.6%	73	27.9%
Cross-disciplinary Co-Authors*	33	12.6%	89	34.0%

* Intra-disciplinary co-authors are those who authored at least 1 publication with another in-Network investigator of the same discipline.
*Cross-disciplinary co-authors are those who have authored at least 1 publication with another in-Network investigator of a different discipline than him/herself.

5.4 Development of Trainees

5.4.1 Progression of Trainees

One of the primary aims of the PS-OC Network is to “train a new generation of trans-disciplinary scientists in the area of physical sciences in oncology". Towards this end, the NCI has placed a strong emphasis on equipping the graduate students and postdoctoral fellows within the PS-OC Network to successfully work in trans-disciplinary teams at the interface between the physical sciences and the life sciences.

The evaluation process has produced data that supports the development and growth of trainees in the relatively new field of physical sciences in oncology. In the period covered – from the start of the program in September 2009 to June 2012 – the number of graduate students involved in projects at the Centers has more than doubled, from 60 to 124 (Figure 5.6). Similarly, the number of postdoctoral fellows involved has also approximately doubled, from 74 to a peak of 141 in December 2011. The involvement of undergraduate trainees has also increased over time. Five undergraduate students were recorded in the first progress report and this has grown steadily to 31 students in the June 2012 report. The PS-OCs also included trainees who were not categorized into either of the groups discussed above (“Other”). The trainees included in this group are reported as medical students, research associates,

research specialist, research technicians, or fellows, As of June 2012, 82 trainees fell into this category, compared to nine in Jan 2010.

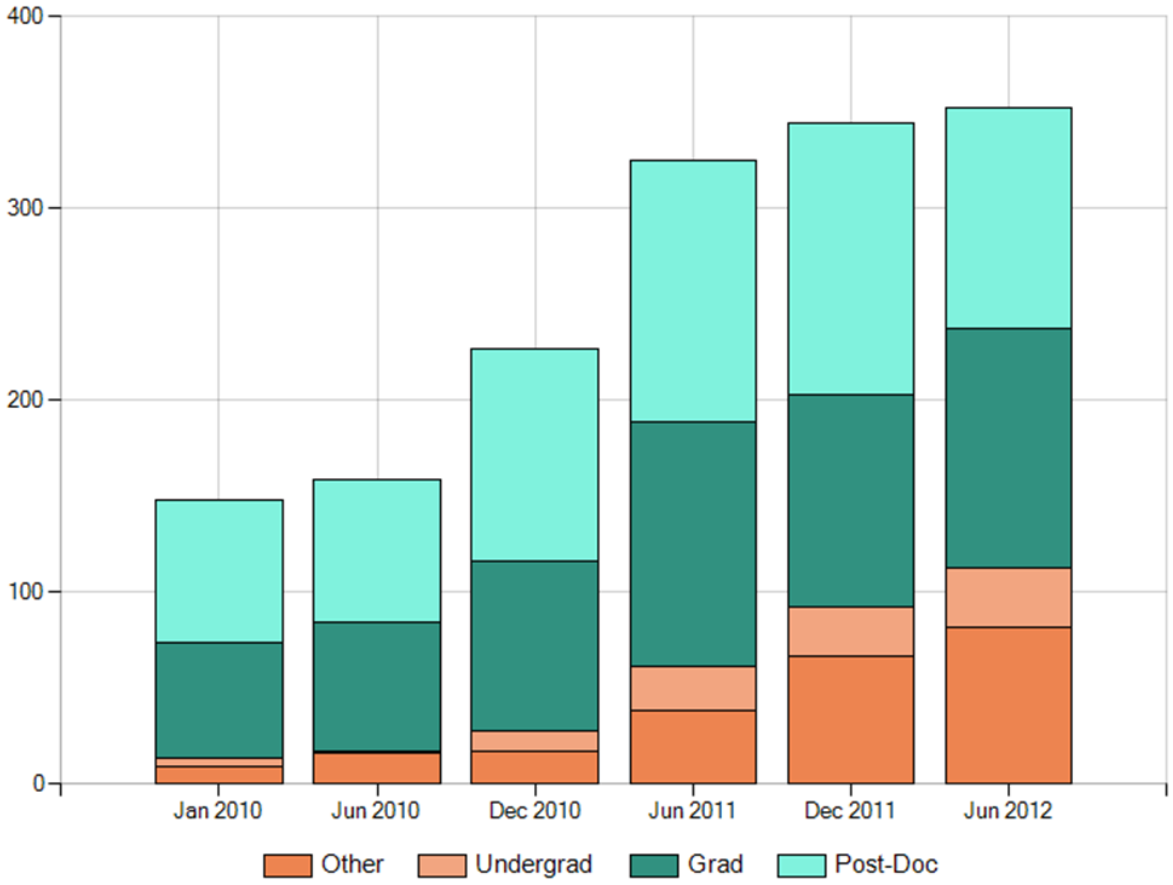

Figure 5.6: Growth of Trainees in the PS-OC Network by Category. The bar charts show the number of Undergraduate, Graduate and Post-Doctoral trainees across the entire PS-OC Network. The data for this chart was derived from the semi-annual progress reports. Individuals listed as trainees but not classified into the groups listed above were coded as "Other" for this analysis.

Overall, all of the 12 centers have contributed to educating and training students over the course of the initiative. In total, 615 trainees have been involved with the PS-OC Network and have been reported through the education and training unit in the progress reports. Each center is comprised of a different ratio of trainees categorized into undergrad, grad, post-doc and "other," which demonstrates the diversity that each center brings to the Network.

5.4.2 CADRE OF TRAINEES IN THE FIELD OF PHYSICAL SCIENCES AND ONCOLOGY

The PS-OC Network consists of trans-disciplinary teams that are approaching cancer research at the interface of the life and the physical sciences. Thus, knowing the academic backgrounds of the trainees is an important piece of information to understand how well the program is working in bringing together these two groups of researchers. To address this question, the progress reports collected information on the academic degrees held by the trainees and this information was used to categorize them as either "physical scientists" or "cancer biologists" (Figure 5.7). This data shows that since the start of the program, about two-thirds of the trainees have a background in the physical sciences. This is consistent with the mission of the PS-OC Program, and though the number of trainees has grown through the course of the initiative, this proportion has remained steady.

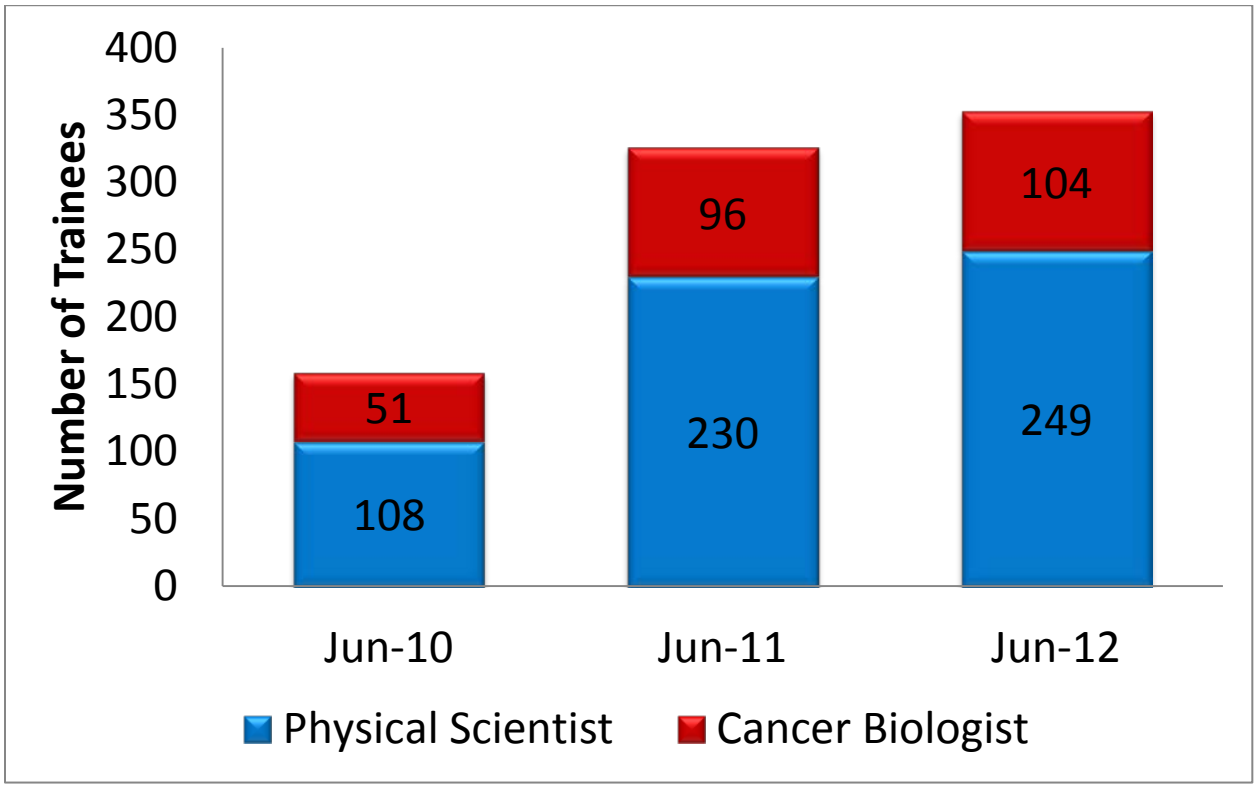

Figure 5.7: Breakdown of trainees by academic discipline. Data from the annual progress reports was used to categorize the expertise of the trainees as either Physical Scientists or Cancer Biologists based on their academic degrees held

5.4.3 PROMOTION OF CROSS DISCIPLINARY TRAINEES - EXCHANGES

Exchanges of trainees between Centers in the PS-OC Network are a key component of the training activities supported by the PS-OC Program. The exchanges encourage the cross-fertilization of ideas between Centers and facilitate the collaborations that are vital to the work of this program. Since June 2010 there have been approximately 40 trainee exchanges reported each year (Figure 5.8) and a total of 113 since the PS-OC Program began.

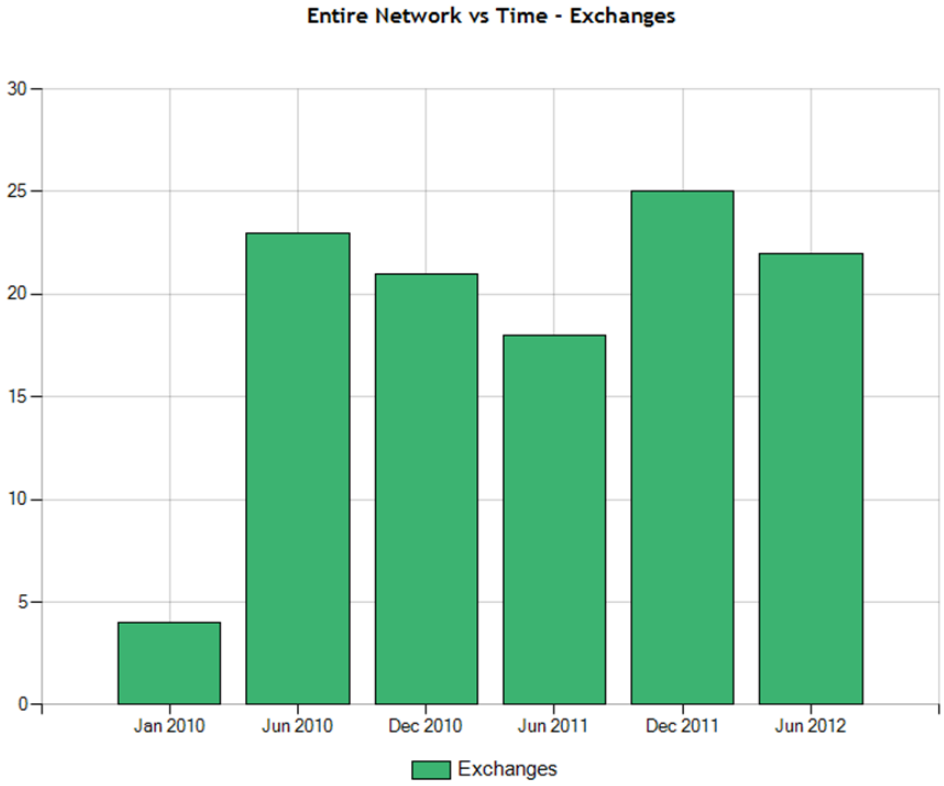

Figure 5.8. **Number of exchanges between PS-OCs.** The chart show the number of new exchanges listed in the Progress Reports submitted on the indicated dates for all the Centers.

The exchanges have benefitted both physical scientists and cancer biologists. For example, a postdoctoral fellow with a computer science background visited the lab of a cancer biologist to learn first-hand about the mouse model of Burkitt's lymphoma developed by that lab. This animal model has since been adopted by the University of Southern California PS-OC to study using computational techniques. As an example of an exchange of trainees with a background in cancer biology, two postdoctoral fellows with from the a cancer biology lab at the University of California, San Francisco, worked in a physics lab at the Princeton PS-OC to learn how they could apply the tools and approaches of physical science, such as microfluidic chips, to their research.

6. Summary and Recommendations

The design and implementation of iTRAQR demonstrates the utility and potential of using a comprehensive web-based system to store and analyze scientific progress reporting data. Key to this process is a carefully developed data model, attention to detail in data entry, and close interaction with the stakeholders. Once the data have been entered and organized accurately, the potential for flexible, high quality research analysis is considerable.

The side-by-side development of a data system with development and testing of collaboration metrics using extant and self-report data has been an effective approach to explore new metrics for team formation, collaboration and knowledge generation, both within centers and across the Network as a whole. There has been significant interest by other NCI programs in the structure of this evaluation, including the logic model, iTRAQR system, and ESR structure, in order to conduct similar prospective evaluations.

Overall, analysis of the collaboration data from progress reports focusing on the effectiveness of PS-OC trans-disciplinary collaborations demonstrate significant progress toward the milestone of establishing an unprecedented Network of centers and trans-disciplinary teams focused on solving cancer problems. Over the first three years of the PS-OC Program, individual Centers have become more integrated and grown to include new disciplines and collaborators and the broader PS-OC nhas become more connected. Additionally, there has been a significant increase in cross-disciplinary publications by PS-OC investigators compared to the years preceding the PS-OC Program.

Training a new generation of trans-disciplinary scientists in the area of physical sciences in oncology is a key goal of the PS-OC initiative. Though the program has only been running for about three years, significant progress has been made in this regard. The trainees (students and postdoctoral fellows) have typically participated in a range of training activities offered by the PS-OC Network. Exchanges have been of particular value to the trainees, by helping to establish trans-Network collaborations and stimulate the exchange of ideas. The PS-OCs have also developed courses aimed either at trainees in the network or more broadly to undergraduate and graduate students outside the Network.

The evaluation has allowed program staff to actively monitor the activities and output of each center. Since the PS-OC Program is an unprecedented initiative, close involvement by program staff allows changes to be quickly implemented which promotes the growth and development of each center and the Network as a whole.