Unintended Effects of Changes in NIH Appropriations:

Challenges for Biomedical Research Workforce Development

Mauricio Gomez Diaz
maugomez@mit.edu
Engineering Systems Division, Massachusetts Institute of Technology

Navid Ghaffarzadegan
navidg@mit.edu
Engineering Systems Division, Massachusetts Institute of Technology
John Glenn School of Public Affairs, The Ohio State University

Richard Larson
rclarson@mit.edu
Engineering Systems Division, Massachusetts Institute of Technology

Last modified: 7-24-12

This work was supported by the National Institutes of Health [Grant 5U01GM094141-02]. This grant, entitled "Developing a Scientific Workforce Analysis and Modeling Framework," was awarded to the Ohio State University and the Massachusetts Institute of Technology (MIT), Center for Engineering Systems Fundamentals (CESF). The discussion and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institutes of Health, the Ohio State University, or MIT.

Unintended Effects of Changes in NIH Appropriations:

Challenges for Biomedical Research Workforce Development

Abstract

The U.S. government doubled NIH appropriations between 1998 and 2003, aiming to foster research activities in biomedicine. However, a series of current indicators demonstrate growing threats to the quality and stability of the biomedical research workforce. Compared to pre-doubling conditions, researchers now spend more time writing grant proposals, leaving less time for carrying out research. Paradoxically, the probability with which a grant proposal is accepted for funding deteriorated sharply after NIH's budget doubling. The average age of first-time NIH grant recipients has increased by almost a decade since the early 70's, while the percentage of biomedical doctorates securing tenured positions continues to drop. In this paper, we develop a system dynamics simulation model of research activities as affected by government grants. We calibrate the model to the historical trends in U.S. biomedical research. Simulating the model, we test and provide support for the hypothesis that a sudden increase in research funds can result in unintended long-term effects hampering research discoveries and workforce development. The model is then used to carry out counterfactual analysis, bringing insights aimed at improving the effectiveness of government research spending.

Keywords: Research workforce development, government research spending, biomedical research, National Institutes of Health

I. INTRODUCTION

The National Institutes of Health (NIH) is the largest funder of medical research in the world and the largest funder of non-classified research in the U.S. federal government (Collins 2011). The agency distributes most of its funding through grants to research institutions, universities, and individuals. Between 1998 and 2003, Congress doubled NIH's budget to over 30 billion dollars annually. The rise in research spending was intended to enhance research production, promote the development of the research workforce, and improve research facilities.

However, several indicators demonstrate not only that the impact of the steep budget increase fell short of expectations; in many cases it might have resulted in unintended negative effects. The dramatic rise in the number of grant applications triggered during the doubling years has not been met with an equivalent growth in the number of available research grants. As a result, success rates for NIH research project grant applications have dropped from 31% in 1998 to 18% in 2011 (NIH RePORT 2012). Due to the increasing levels of competition, the percent of early-career NIH grant awardees declined from 23% in 1998 to 15% in 2005, affecting workforce development and young researchers' promotion in academia (Teitelbaum 2008).

Studies show that despite the doubling in NIH's budget, the trend in the number of biomedical publications by U.S. scholars has not changed when compared with the overall global publication trend (Sachs 2007). Less productivity and underwhelming output negatively affects political support for further budget increases. As tougher competition and lower success rates fuel pressure for further increases in funding, declining productivity and disappointing results translate to waning political support for the NIH.

These outcomes illustrate the complexities inherent in the common assumption that large funding increases should result in equivalent rises in research output, high quality scholars, and a more attractive perception of research careers. In this paper we layout the complex network of effects of funding on research activity and workforce development. Our focus is on biomedical research in the U.S., using NIH's budget doubling between 1998 and 2003 as a case study. We discuss how the current indicators that suggest a need for additional funding can be side effects of the preceding sudden budget increase and subsequent stagnation. We develop a simulation model, replicate the historical trends in the U.S., and provide policy insights aimed at improving the outcomes of NIH funding.

II. CHALLENGES AND COMPLEXITIES

In 1997, the U.S. Senate voted 98-0 to endorse the goal of doubling the NIH's budget in five years (Pear 1998). The project was successful; between 1998 and 2003 Congress doubled NIH appropriations from \$13.6 billion to \$27.1 billion (Smith 2006). Figure (1) illustrates this trend in constant 2010 dollars highlighting the relevant period.

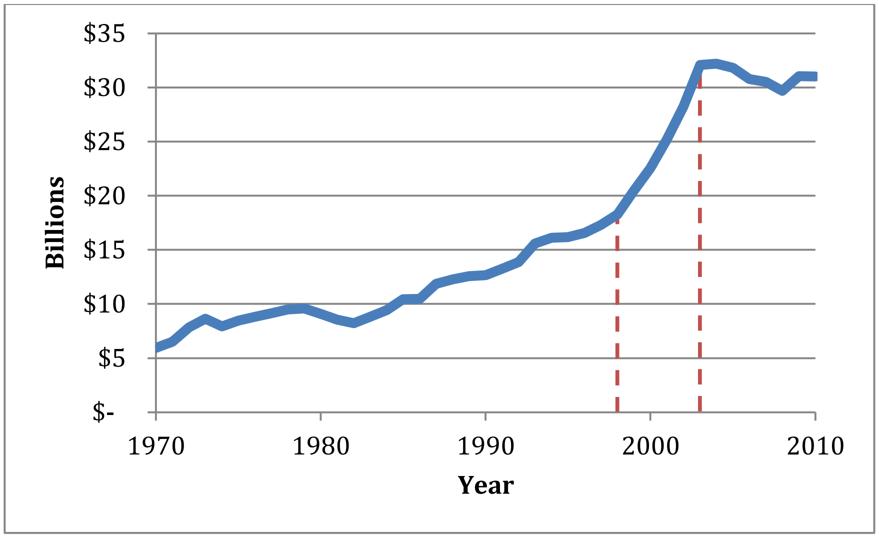

Figure (1): NIH budget in constant 2010 dollars.

Source: http://officeofbudget.od.nih.gov/approp_hist.html

The budget doubling flooded NIH with billions of dollars over a relatively short period of time, provoking a massive expansion in biomedical research. Achieving the doubling of NIH budget in five years required an annual growth rate of roughly 15% (Kaiser 2003). Such steep budget growth created the conditions for a comparably steep increase in the number of researchers, particularly at the doctorate level. Consequently, expectations of federal support surged to levels that could not be sustained once the budget stopped growing (Couzin and Miller 2007). The biggest strain on the budget ultimately came from this general increase in researchers (Timmer 2008).

The swelling budget drove institutions to spend their own money building more research laboratories in anticipation of winning NIH grants to operate them (Brainard 2004). Universities added graduate students and postdocs in biomedical departments, increasing the pool of researchers competing for NIH grants (Monastersky 2007). The dramatic surge in demand for researchers was met with a growth in supply, creating a scenario in which stability depended on continuous annual budget increases of 15%. Sustaining this growth was not only practically unfeasible; policy-makers never intended it.

Once the double-digit growth ended, biomedicine found itself in a situation where the supply of qualified researchers far outstripped demand. NIH's budget underwent an abrupt reversal after 2003, going from annual increases of 15% to boosts of around 3% in the years to follow; a decline in real terms when accounting for inflation. Stagnant funding levels, combined with inflation, resulted in a 13% decline in NIH's purchasing power between 2003 and 2007 (Agres 2007). Not unexpectedly, such a severe shock resulted in a wide array of negative effects for the biomedical research community. In 2007 Science magazine concluded that conditions worsened after NIH's budget doubled, as the infusion of money was far too rapid and not tied to structural reforms that could have enabled NIH to best use its growing resources (Benderly 2007).

2.1. Troubling Indicators

This case study illustrates how the rapid growth of NIH's budget, a seemingly positive event, set the stage for a series of unintended negative effects due to the complex interactions between different components of the system. Among these effects, we find that the current stagnation in available grant awards, coupled with the increase in applications, has resulted in declining success rates. Figure (2) shows how this decline began shortly after the doubling efforts came into effect in 1998.

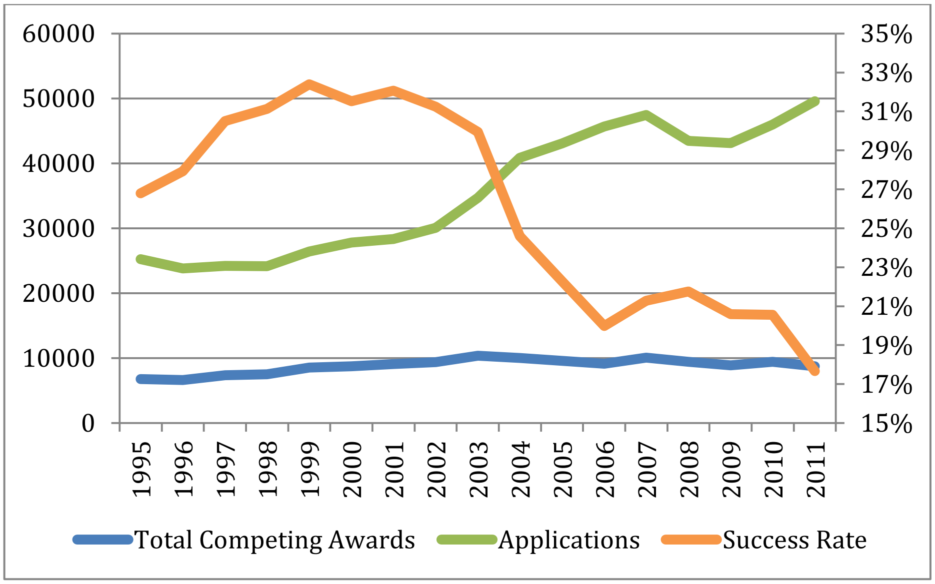

Figure 2. Competing awards, applications, and success rates.
Source: FASEB, NIH Research Funding Trends

A second troubling indicator closely related to the decline in grant success rates is the rising age at which investigators secure their first R01 or equivalent grants. These types of grants are a critical milestone in a researcher's career, and are essential for their establishment in the scientific community. Figure (3) shows this rising trend, where we can also appreciate a steep increase shortly after 1998.

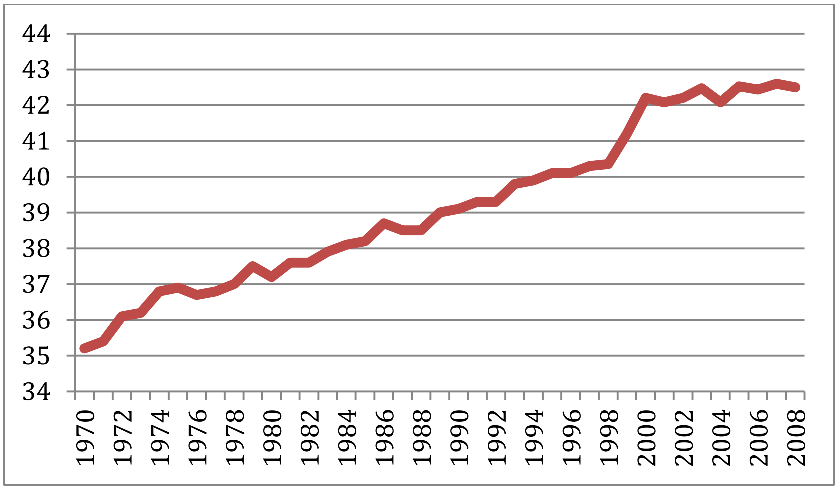

Figure 3. Average Age of First Time R01 Equivalent Investigators
Source: FASEB

Other similar indicators include the increasing number of postdoctoral researchers, toughening competition for PhD graduates seeking academic jobs, and a rising trend in non-tenured positions at universities. In addition, assume that in equilibrium the top X % of candidates enter the biomedical system as PhD candidates. If the number of available PhD slots were to double, then the top 2X % of candidates would enter the system, therefore impacting the quality of the talent pool. Given NIH's commitment to a stable and sustainable scientific workforce, the agency is growing increasingly concerned about the troubling indicators outlined above (Ruiz Bravo 2007). Without formal and verified models that broadly describe such systems, identifying effective policies and foreseeing unintended side effects remain elusive tasks.

In light of the unintuitive consequences that budget increases can bring, our goal is to examine how the NIH and its funding levels affect the development of the U.S. biomedical research workforce. The analysis will focus on understanding how different variables interact, respond to each other, and generate feedback mechanisms that ultimately give rise to unforeseen behavior.

III. MODELING

Fostering research and boosting scientific discoveries are the main motivations for federal research spending. In the absence of adequate levels of funding for biomedical research, different political, civil, and academic constituencies can put pressure on government to increase its support. Government responds to this pressure by investing in research through the NIH. Such an investment is expected to help the biomedical research community, foster discoveries, and fill the gap between the perceived and desired levels of scientific progress.

Increasing NIH's budget can enhance biomedical research production through two main mechanisms, shown in Figure (4). First, additional funding allows current researchers to focus on research projects, purchase better equipment, attend conferences, and spend more time on research (for example, during summers). In other words, research funding increases the average research activity carried out by current researchers (Loop B1, in Figure 4). Second, additional funding can be used to support new graduate students and postdocs, who will then contribute to research activities (Loop B2, in Figure 4). Altogether, more researchers, and more research activity per researcher, increase total research activity, leading to more research discoveries. This structure, consisting of two balancing loops (B1 and B2) provides a goal seeking behavior where government invests on research in order to fill the gap between the current and desired levels of biomedical research discoveries.

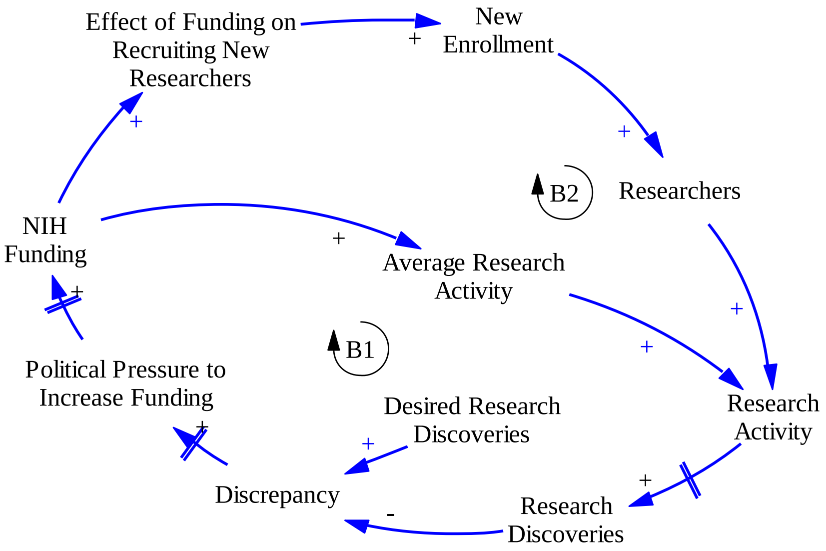

Figure 4. Investment made to enhance scientific discoveries

The ecosystem of biomedical research production is more complex than what is presented in Figure 4. There are several major reinforcing mechanisms in the system that can result in a series of vicious, or virtuous, cycles and counter the effects of increased government spending. In addition, there are other balancing mechanisms that lead to policy resistance, slowing down research progress in biomedicine or leading young researchers to drop out from the research workforce. In the following section we discuss these two sets of sub-structures.

3.1. Reinforcing Mechanism of Grant Writing Activities

A series of feedback mechanisms influence the submission of grant proposals and therefore affect the overall research production. We will discuss six major reinforcing mechanisms. First, while we intuitively expect the percentage of grant proposals that are funded to increase with additional research funding, in the long run the number of grant applications will also increase. As government funding increases, the number of new researchers supported through NIH grants as students, research assistants, and postdocs, will also increase. This translates to a growing number of future grant applicants, impacting the future success rate of grant submissions. Since it takes time for new researchers to become future grant applicants, there is a delay in the effect of this countering mechanism.

The period of budget doubling witnessed a dramatic increase in the number of applications for NIH grants that was met with a corresponding increase in the number of grants. Once the doubling ended, the continuing growth in applications was met with a stagnant number of grants. Science magazine reported that increased funding helped drive more applicants to NIH, and the chances of being funded by the agency on a first attempt plummeted from 21% in 1998 to 8% in

2006 (Couzin and Miller 2007). A growing biomedical research workforce increases the number of applicants for NIH grants, which results in a larger applicant pool and drives grant success rates down. This loop is depicted in Figure (5) as R1.

Second, lower success rates drive researchers to submit more applications, leading to even lower grant success rates. During the budget doubling, the number of applications grew at an even faster clip than the number of potential applicants, as scientists, concerned about their chances of getting funded, began submitting proposals more frequently (Couzin and Miller 2007). This behavior underscores a natural response of individuals to decreasing success rates. As the percentage of researchers funded drops, the perceived competition for funding increases. Higher competition drives applicants to submit even more applications in order to enhance their chances of receiving a grant. As the numbers of grant applications per applicant increase, the total applications submitted will also increase and further drive success rates lower. This creates a dangerous reinforcing feedback loop in the system that is depicted in Figure (5) as R2.

The third and fourth mechanisms emerge from the fact that a higher level of competition for grants demands higher quality applications. More applications per applicant, of increasing quality, unequivocally result in more time spent by researchers writing grant applications. This mechanism drives researchers away from research and into grant writing, affecting the overall research production. In 2007, “Robert Siliciano, an infectious disease expert at Johns Hopkins University School of Medicine, told the Senate panel the reduction in NIH grants has forced him to scale back on promising research into optimizing antiretroviral therapies. ‘Typically, in the past, I would spend about 30 percent of my time applying for grants; now about 60 percent of my time is spent preparing applications’ he said” (Agres 2007).

The need for submitting more applications affects not only the amount of time available for scientists to perform research, but their attitudes towards research. Also in 2007, Stephen M. Strittmatter, a professor of neurology and neurobiology at Yale University's School of Medicine, told legislators that due to increased competition, "researchers shy away from real discoveries. They've become worriers, not explorers" (Agres 2007). It is straightforward to infer that these consequences of spending more time writing grant applications negatively impact the rate of successful discoveries made by the biomedical academic workforce. This, by itself, is clearly an undesirable outcome. In Figure (5) R3 depicts the effect of writing more applications per applicant, while R4 illustrates the impact of higher competition on the quality of these applications and therefore on the available time for research.

The fifth reinforcing mechanism is related to the institutional pressures on biomedical researchers to attract funding. An increase in NIH funding triggers a crucial reinforcing feedback loop in which, as NIH funding increases (or decreases), universities’ expectations from researchers to bring a portion of available funds increase. Universities are willing to make large investments to expand their infrastructure if they see that there is a growing pool of funds available to support such investments. Expectations for increased funding lead to expansion, both of infrastructure and personnel. This effect was observed during the budget doubling period: “Research institutions everywhere were breaking ground on new facilities and expanding their faculty […] to fill the buildings, expecting to recoup their investments from the NIH grants investigators would haul in" (Couzin and Miller 2007). This phenomenon is illustrated in Figure (5) as R5.

Finally, the desired level of overall research production is not a constant figure, and can change in response to the situation at a given point in time. The phenomenon is similar to Forrester's floating goal in his market growth model, and is depicted on Figure (5) as R6.

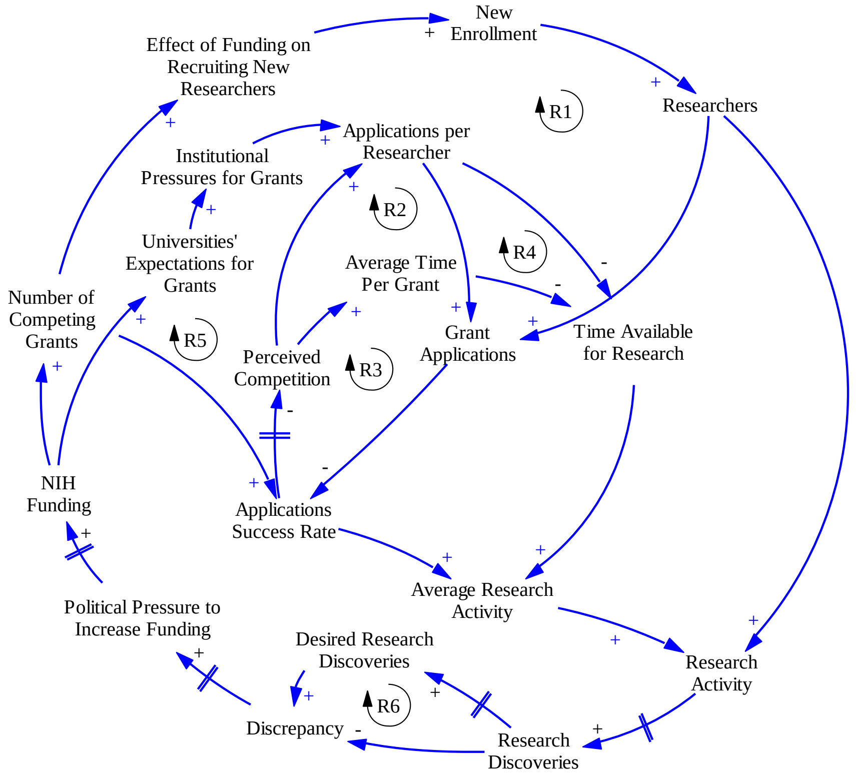

Figure 5. Reinforcing mechanisms countering the basic goal-seeking loops

3.2. Balancing Mechanisms against Research Attractiveness

The complexity of the system increases when we consider researchers' perceptions and responses to changes in their work environment. Funding opportunities and the time that investigators spend writing grants are highly relevant determinants of the attractiveness of a research career. In 2007, Edward Miller, dean of Johns Hopkins Medicine, told a Capitol Hill news conference: "We are seeing young researchers quitting academic research in frustration, having concluded that their chances of having innovative research funded by NIH are slim to none" (Agres 2007). Furthermore, being able to secure NIH grants is an essential professional step for young biomedical researchers seeking tenured positions at U.S. colleges and universities. It is common for young faculty members to win two to three R01 awards to support a lab before they can gain tenure (Monastersky 2007). As success rates drop, the amount of time taken for researchers to secure sufficient grants rises, lengthening the average training period typically at the increasingly common postdoctoral stage. Longer postdoctoral appointments further impact the attractiveness of a research career: “Graduate students see long periods of training, […] they get a sense that this is a really frustrating career path…" (Monastersky 2007). The effects that these variables have on the attractiveness of a research career are illustrated in Figure (6). Dropout rates are affected by the attractiveness of a research career, which in turn is affected by grant success rates, average promotion periods, and time available for carrying out research.

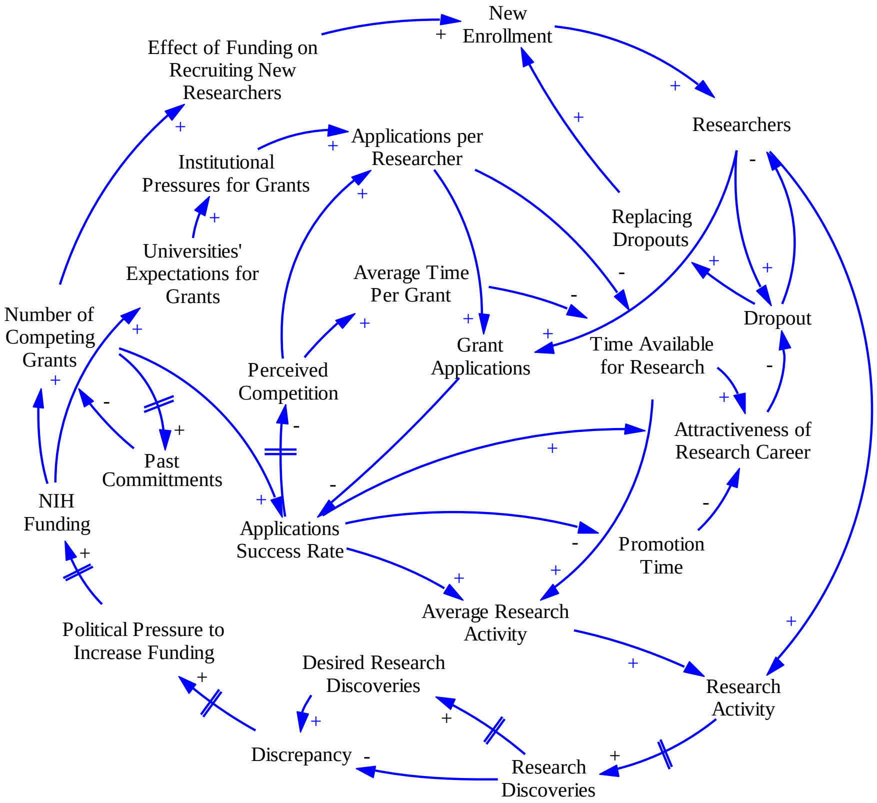

Figure 6. Attractiveness of research career as affected by feedback loops

In theory, the balancing feedback loop that results from falling attractiveness and increasing dropout should counter further increases in the number of biomedical researchers. The biomedical workforce system, however, is not closed. “Given increased research funding, additional graduate students and postdocs can be readily recruited from large potential pools in countries with fewer such opportunities— precisely what took place as the NIH budget was rapidly doubled” (Teitelbaum 2008). The expected consequences of lower success rates, longer promotion times, and increased time writing grants, are therefore attenuated in this system given its open nature; a drop in attractiveness does not necessarily result in a reduced supply of researchers. This effect is shown by the link from ‘Dropout’ to ‘Replacing Dropouts’ and ’New Enrollment’ in Figure (6). This mechanism may affect higher quality researchers disproportionally as they can more easily switch careers while their positions are filled by less experienced substitutes.

Figure (6) also introduces the concept of past commitments (the balancing loop around the number of competing grants and past commitments). When a researcher is awarded an R01 or equivalent grant, he or she will not receive the entire grant’s worth on the first year. Since these grants typically span periods of four years, projects will receive approximately one-fourth of the entire grant each year. The amount of financial resources available for new grants therefore depends both on that year's budget and on previous financial commitments. This is important because the commitments made by NIH during years of unusual budget growth can extend to subsequent periods of financial stagnation. When this happens, the availability of funds for new grant awards is severely diminished so that previous commitments can be met.

3.3. Operationalizing for Simulation

In order to create a simulation model of the biomedical workforce, a few modifications to the above formulation are needed. Researchers tend to behave differently in different stages of their careers, in particular before and after getting tenure. In order to distinguish their behavior and still avoid making the model overly complex, we disaggregate the 'Researchers' variable in two main variables: young researchers and established researchers. This is a simplification of the actual pipeline, in which researchers go through several more stages: PhD candidates, postdoctoral scholars, assistant professors, associate professors, tenured professors, etc. The dynamic complexities caused by the delays involved in career progression, and their impact on the overall system, are nonetheless captured by reducing these stages to the two stocks mentioned above.

The stock of young researchers includes those professionals who are yet to receive enough grants to support a lab or achieve tenure. While it is rare for established researchers to leave academia, young researchers dropping out of academia is a critical outflow and is therefore included in the model. In contrast, the established researchers stock represents researchers who have plenty of experience, are well positioned, and have achieved tenure; they have little incentive to leave academia. Figure (7) shows how researchers are presented in our model.

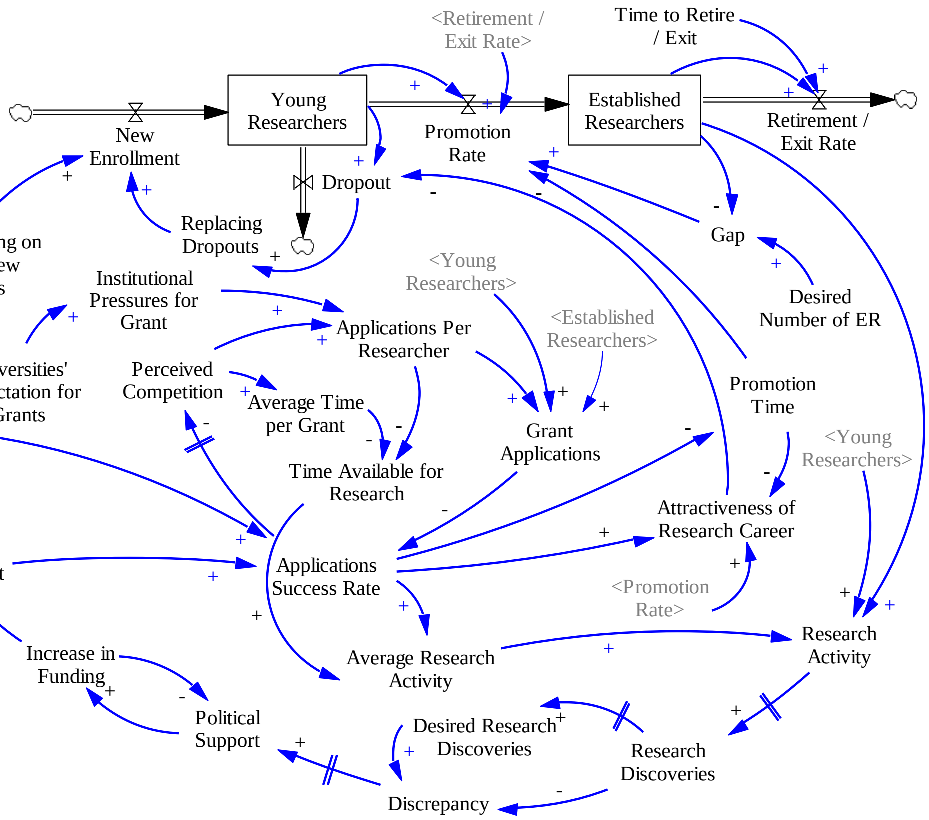

Figure 7. Final causal loop diagram

Stocks of researchers at different career stages and financial commitments in dollar amounts are easy to conceptualize given the tangible nature of their units. Other more abstract concepts, however, also need to be modeled if they are deemed to play a critical role in the real system. Political support, as illustrated in Figure (7) is one such concept. Even though the feasibility of quantifying historical levels of buildup and depletion of political pressure is debatable, the intuition behind this structure is straightforward. A growing discrepancy between desired and actual levels of discoveries increases the inflow of pressure into the stock, resulting in its accumulation, while pressure is released after increases in budget. The rates of pressure inflow or outflow depend on the magnitude and duration of funding stagnation or increase. While the units in which political pressure is measured will not have any tangible meaning, the behavior of this structure is of critical importance to the system.

The system described in this section contains pervasive feedbacks and delays that give rise to high levels of complexity (Richardson 2011). The causal diagram of the system provides a platform to capture complexities in the biomedical system and discuss the sources of resistance to policies that at first glance might make sense. In order to understand and avoid troublesome side effects, leverage its feedback mechanisms, and make a positive impact in this complex workforce system, it is essential to make use of computer modeling and simulation methodologies (Ghaffarzadegan, Lyneis, Richardson 2011). The notion of designed experimenting in the real-life system is clearly impractical and unfeasible, while computer-aided simulation renders experimentation feasible (Sterman 2000).

The boundary model is purposefully set around biomedical research workforce development to capture a more accurate representation of the dynamics. The doubling policy is operationalized as a pulse function that is activated between 1998 and 2003 in the base run.

Following this thread, the described model is formulated in Vensim. The file is provided as an online supplementary to this submission. The model belongs to the family of models of research workforce development (Sterman 2000, Larson and Gomez 2012, Ghaffarzadegan, Hawley, and Desai 2012). In contrast to previous models, our model is structurally focused on capturing the dynamics of research spending and research activities, tailored to study the effects of a specific government budget policy. We parameterize the model for the specific case of biomedical research workforce as affected by NIH research grants and calibrate the model to replicate the trend over the past four decades. Values of all parameters are available inside the Vensim file.

IV. SIMULATION

4.1. Base run

In order to validate the behavior of the model, its output is compared to U.S. historical data between 1970 and 2012. Figure (8) shows how NIH's budget in the simulation closely follows the trend in the average historical rate between 1970 and 1998. The decision to double NIH's budget in 5 years is considered exogenous to the model and therefore the yearly increases during that period are added exogenously. The decline in NIH budget after 2003, however, is the model's endogenous response to such an unprecedented period of growth. This decline is largely a result of the depletion of political support during the doubling years, leaving little political will to push for subsequent increases. The budget starts to recover a few years later, after enough political support accumulates once again, but experiences renewed stagnation given the economic woes suffered after 2008.

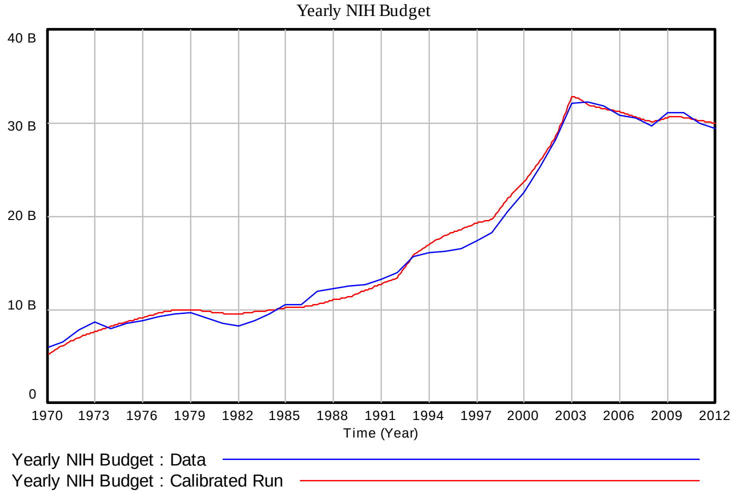

Figure 8. NIH's Yearly Budget,
Actual and Simulated

In terms of the number of grant applications received by NIH during this period, Figure (9) shows that the simulation replicates the growth experienced shortly after 1998. The simulation does not exactly follow the same growth pattern, in which there was an initial moderate increase followed by a steeper rise. Furthermore, the data also shows a brief drop in the number of applications in 2007 that the model does not replicate. This could have been caused by factors not considered in the model, which is expected given the unfeasibility of accounting for all variables that affect the real system. Nonetheless, the model shows how the number of applications decelerates after the doubling is completed but continues to grow, outpacing the stagnating budget after 2003. The data suggests a similar behavior after the brief decline in 2007. The available data for applications per applicant and success rates give further context to the troubling situation that the workforce experienced during the post-doubling years.

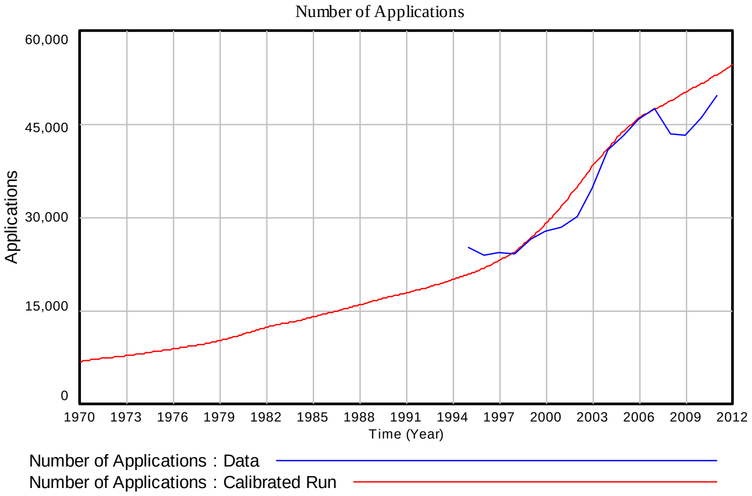

Figure 9. Number of Grant Applications Received
by the NIH Each Year, Actual and Simulated

Previously we described how an increase in grant applications is not only the result of a growing research workforce, but also the consequence of a considerable rise in the average number of applications submitted by each grant applicant. Figure (10) shows how the simulation output compares to the available, albeit sparse, data. In the simulation, a jump in this number coincides with the beginning of the budget doubling period; the corresponding jump in the data happens slightly later. Again, the number of applications per applicant undergoes an initial moderate increase followed by steeper growth that is not replicated by the model. The overall behavior, however, is captured in the simulation.

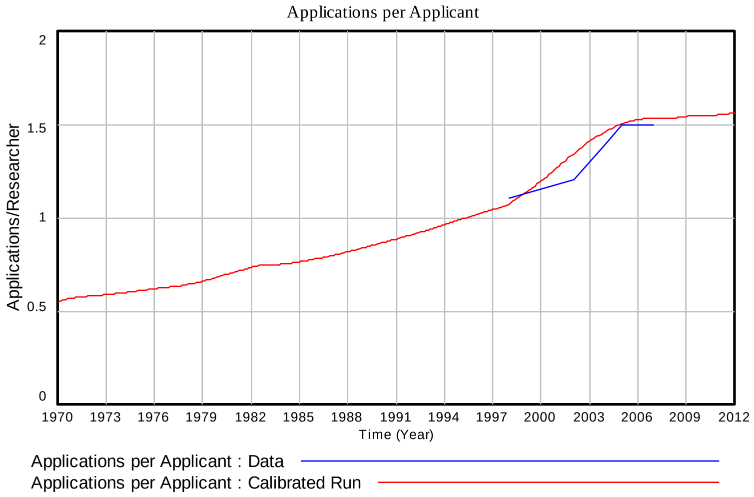

Figure 10. Average Number of Applications Submitted per Applicant, Actual and Simulated Data

As for the number of competing awards available, Figure (11) shows how the simulation replicates the growing trend in the historical data followed by stagnation. Even though the short-term oscillations in the historical data are not entirely captured by the simulation, the overall match is satisfactory. It is worth noting that the NIH raised the average grant size during the doubling years to avoid creating an unsustainable number of awards (Kaiser 2005). This is considered in the model and helps explain why the increase in competing awards is not as steep as the increases in budget. It also reveals NIH's awareness of some of the potential destabilizing effects associated with changes in funding, supporting the hypothesis presented above regarding the jump in postdoctoral salaries. The magnitude of these destabilizing effects, however, proved to be much larger than expected in light of the outcomes discussed throughout this study.

The stagnation in budget and competing grants, coupled with a continuously growing number of applications, foreshadows the behavior of the success rate curve. Figure (12) shows how the simulation captures oscillation in success rates, a small short-lived increase during the doubling years, and a dramatic drop that matches the historical data. Even though the simulation does not exactly replicate the timing and steepness of actual changes in success rates, it does reflect the overall oscillating and declining behavior.

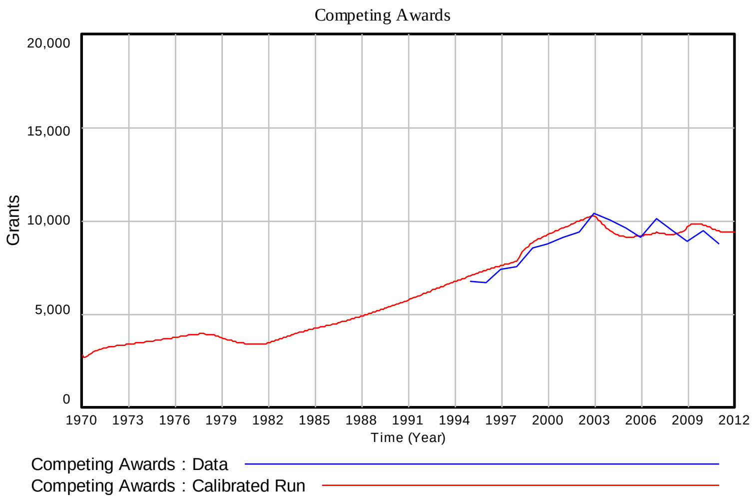

Figure 11. Number of Competing Awards,
Actual and Simulated

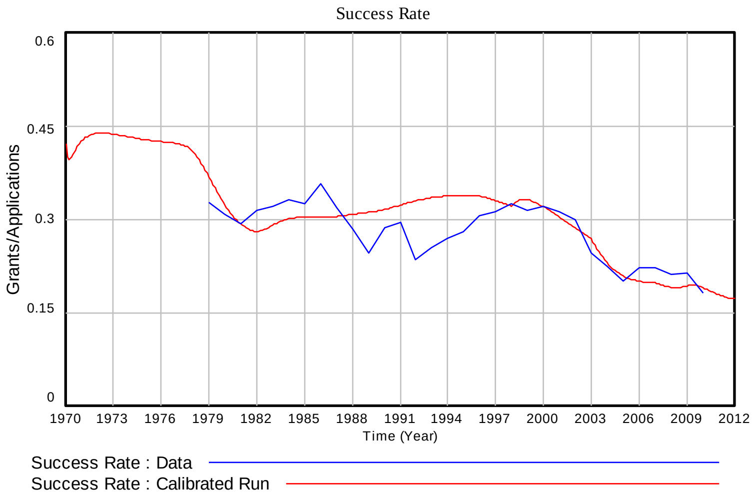

Figure 12. Grant Awards Success Rate,
Actual and Simulated Data

4.1. Policy Analysis

The development of mathematical models such as the one presented in this paper is, on its own merit, a process that greatly improves the understanding of the underlining system. A major benefit of the modeling effort, however, is the possibility of simulating a series of policy scenarios and examining the model's overall response to such changes. This section therefore explores a series of counterfactual scenarios that answer "what if" questions regarding the absence or implementation of different policies, particularly related to funding. Since the model consists of a large number of parameters that can be modified, this analysis is limited to changes in variables concerning policies that decision-makers within government, and within the NIH, can implement.

Given that this paper focuses largely on the effects of doubling NIH's budget and its aftermath, the first scenario explored is one in which this steep increase doesn't take place. To operationalize such scenario, experiment #1 consists of turning off the exogenous input used to replicate the unprecedented inflow of funds between 1998 and 2003. The resulting budget outcome is shown in Figure (13). This experiment shows that without the doubling, funding levels would have surpassed those in the calibrated run shortly after 2009. In current dollars, this translates to an annual growth rate of approximately 8%. FASEB officials reached a similar conclusion in 2006, when they calculated that NIH's budget would "soon stand at the same point it would have reached if it had simply continued its historic rate of growth"(Mervis 2006). The simulation also shows how the exogenous impact of an economic downturn would have been comparably smaller given that political support would not have been depleted after 2003.

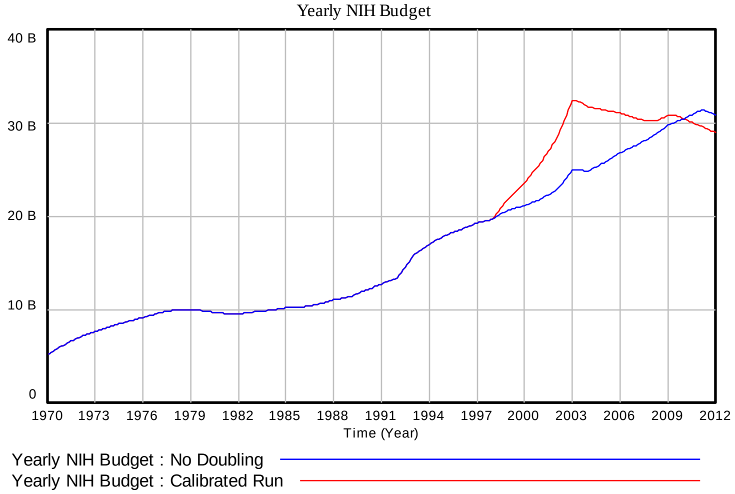

Figure 13. Experiment #1: NIH Budget

To understand the wider effects of not doubling the budget, a series of outcomes related to grants are first examined in Figure (14), focusing on the 1997-2012 period. The number of competing grants in this counterfactual experiment is initially lower but steadily grows beyond the number in the calibrated run. The exogenous economic shock causes a delayed but steeper drop in competing grants given that the average grant size is held constant in the experiment. As for the number of applications per applicant, the experiment shows a much smoother increase. Although an increase in this variable is still troubling, it is certainly preferable to have its growth be more moderate. This results in a decreased number of total grant applications, which also grows at a lower rate. Finally, success rates remain considerably higher throughout most of the examined period. The sudden drop near the end is a response to the drop in competing awards, which can be ameliorated by modifying the average grant size as was done by the NIH during the doubling.

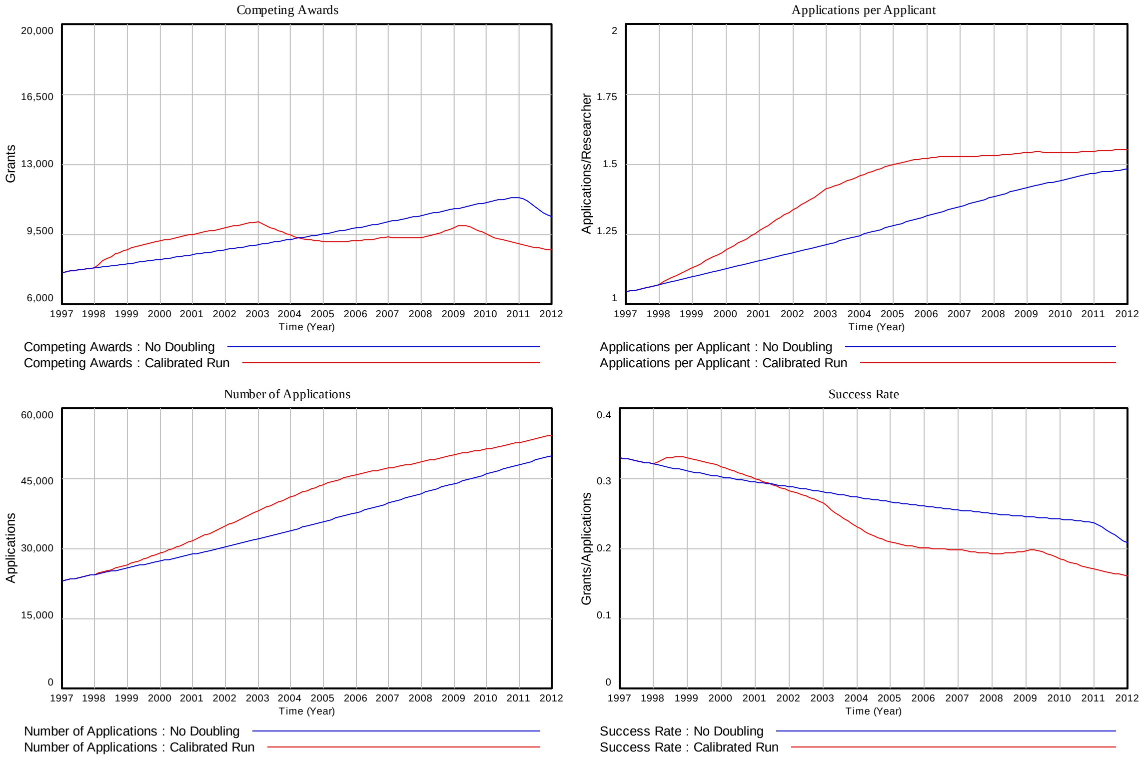

Figure 14. Experiment #1: Competing Awards, Applications per Applicant, Number of Applications, and Success Rate

The outcomes related to research output and productivity are examined in Figure (15). Despite the consistently lower budget in the experiment, it shows a relatively unchanged level of research activity, measured in total hours per year, compared to the base case. The total number of researchers and the time spent by them writing grants are factors that influence this aggregate research activity. In the counterfactual run, researchers spend less time writing grant applications, which explains why even though funding is lower and the number of researchers is smaller, research activity remains relatively unchanged. These outcomes also help explain why productivity, measured as research activity per dollar spent, remains significantly higher throughout most of the examined period. The jump in productivity in the calibrated run shortly before 2010 is caused by the drop in funding due to the exogenous economic shock. This shock affects the experimental run with a delay, which is why productivity starts to rise almost 2 years later in this case.

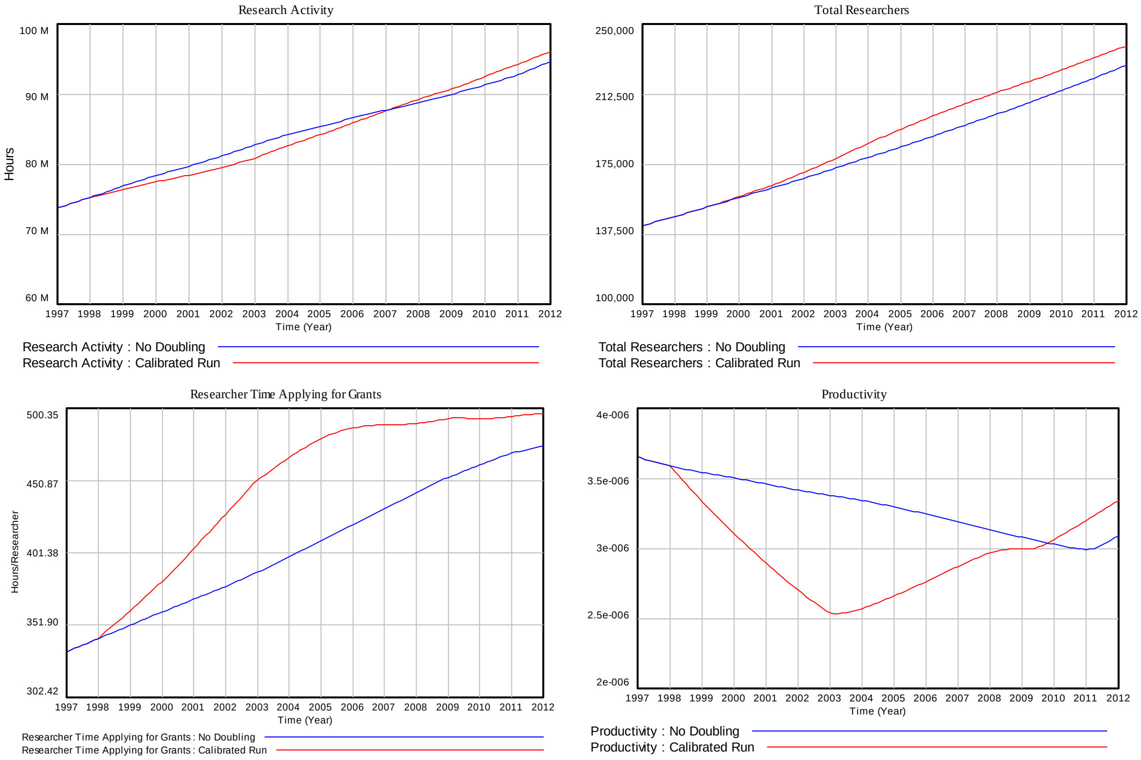

Figure 15. Experiment #1: Research Activity, Total Researchers, Researcher Time Applying for Grants, Productivity

The U.S. Congress holds the final decision regarding yearly NIH appropriations, which renders the first scenario tested one that the NIH can influence indirectly through budget requests but not determine directly. A series of additional experimental policies are therefore proposed, including one that the NIH has greater control over. The outcomes of these experimental policies are then presented side-by-side with the calibrated run and the historical data for ease of comparison.

The second experiment tackles the issue of training more scientists than the workforce can support in the long term. Doing so leads to an imbalance between supply and demand of professional academic researchers, among other negative consequences (Ripple Effects Communications Inc. 2012). An increased number of graduate students were supported with the large influx of funds that the NIH started to receive in 1998. As argued earlier, this new wave of students will eventually become grant and job applicants, impacting competition and success rates.

Experiment #2 therefore tests a policy in which a cap is imposed on the number of graduate students that can be supported through NIH grants. This policy is designed to accompany large budget increases such as the one experienced between 1998 and 2003, and is relaxed during periods of budget stagnation. To operationalize this experiment, the average fraction of students supported by a typical NIH grant is reduced by 50% between 1998 and 2003.

The third experiment addresses the problem that arises when the number of new grants awarded by the NIH each year undergoes volatility. Increases in the number of grants awarded during periods of financial prosperity represent commitments that can spill over to periods of stagnation.

This reduces the availability of new grants, inducing volatility and destabilizing the system. As mentioned above, the NIH attempted to ameliorate this issue during the doubling years by increasing the average grant size. An alternative approach is tested in this experiment.

In order to dampen the undesired effects arising from variance in the number of grants awarded by the NIH, experiment #3 tests a policy that fosters smooth and sustained growth in their number each year. Under this policy, financial resources exceeding the level required to support this sustained growth are not spent on additional grants. Instead, such additional funds are used to create a financial buffer aimed at maintaining grant stability during periods of budget cuts. This policy is implemented by creating a new stock of financial resources, thereby modifying the structure of the system. Inflows to this stock occur when the available funds exceed what is needed to maintain a given level of yearly growth, while outflows take place when additional funds are needed to maintain this level.

The outcomes to experiments #1, #2, and #3 are plotted together in Figure (16) along with the calibrated run. Bear in mind that the only changes in each of these experimental runs are the ones discussed in the paragraphs above, i.e. in #2 and #3 the exogenous efforts to double the budget between 1998 and 2003 still take place.

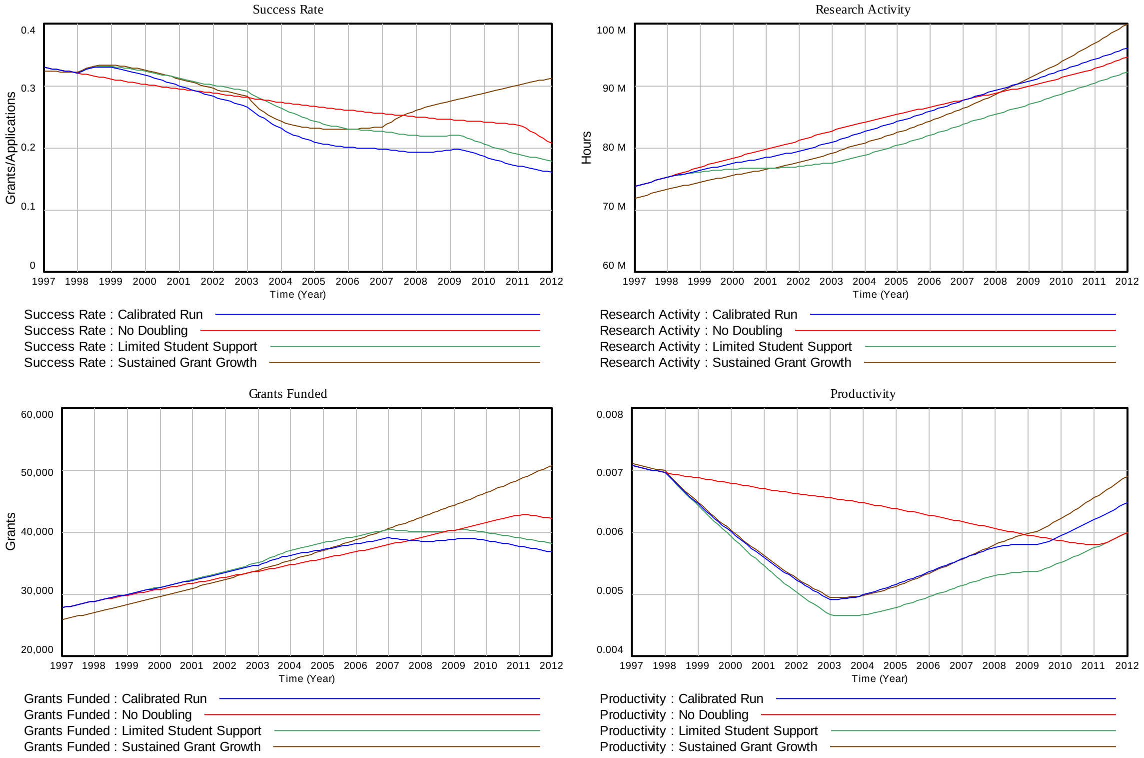

Figure 16. Major Outcomes of Experiments #1, #2, #3, and Calibrated Run

Limiting student support when the budget experiences steep growth results in a moderate gain in success rates, compared to the base case, due to the reduced number of grant applicants. The tradeoff, however, is that with a smaller pool of researchers, the aggregate level of research activity also decreases even though the number of grants funded is slightly higher. As a corollary, experiment #2 also has the lowest levels of productivity throughout the examined period. This policy's relatively straightforward implementation makes it an attractive option, but it is critical to carefully evaluate whether its benefits for success rates outweigh its costs in research output.

In contrast, the implementation of the policy tested in experiment #3 is significantly more complicated; it requires a change in the system's structure, with all the political obstacles that such a change entails. Its benefits, however, are consistent throughout the examined outcomes. Success rates maintain relative stability during the years following the budget doubling due to the sustained growth in the number of grants available. This results in higher productivity after 2009, not only due to the drop in spending, but also due to the continuously growing level of research activity. This is a change that could transform the overall behavior of the system in the right direction, inducing greater stability and enhancing the development of the research workforce.

V. CONCLUSION

Through the implementation of a system dynamics model, this study has shown how a sharp and temporary rise in NIH funding can result in unintended negative consequences. An increase in funding, and the corresponding growth in the number of grant awards available, results in a larger pool of graduate students and researchers entering the system. With additional researchers in the system, the number of applicants for NIH grants eventually increases. If the growth in funding stagnates, or even decelerates, the previous growth in applicants will result in lower grant success rates and therefore in increased competition. Higher competition levels translate to additional time spent writing grant applications, which eats into valuable research time. All these effects have a negative impact on the attractiveness of a research career, hurt productivity, and imperil the stability and availability of the future workforce.

The side effects described above are not inevitable and a series of strategies can be implemented to prevent them. Perhaps the most salient lesson arising from this study is that sudden and significant changes in funding levels have the potential to severely destabilize a system that is already vulnerable to oscillations due to multiple feedback loops and delays. The negative effects of a stagnant or decreasing budget can be intuitively foreseen, but for steep and short-lived growth these effects are not as intuitive. Sustained, smooth, and therefore predictable growth levels in funding, foster the conditions for the necessary stability in the system. Stability can play a crucial role in preventing high levels of competition and frustration, stimulating productivity while building a more favorable perception of a biomedical research career. The unpredictable reality of political decisions, however, poses a real obstacle to ensuring stable and uninterrupted budget growth.

Other alternatives can help stabilize the system without the need for an outright political assurance of sustained budget growth. Among these are the modifications of policies that exacerbate the impacts of volatile funding, such as the requirement imposed on NIH to fully utilize its annual appropriations every year. Whereas private corporations are able to manage financial windfalls and conserve some resources for the future, NIH must spend nearly all the money it receives the year it receives it by law (Couzin and Miller 2007).

Under the current system, sudden growth in NIH's budget translates to a direct increase in the annual number of grants awarded. Each grant awarded represents, on average, a 4-year financial commitment by NIH to the underlining project. Reduced availability of new grants, coupled with a growing workforce size, intensifies the effects of a sluggish budget. If the agency was given more freedom to manage its budget under a longer time horizon, much like a corporation, the volatility of year-on-year political decisions could be attenuated, enhancing the stability of the system.

The previous discussion also highlights the impact of NIH's budget on the overall size of the workforce and the real potential for generating an oversupply of researchers following sharp budget increases. Accounting for these systematic effects, instead of freely allowing the use of NIH grants to sponsor unusual waves of new graduate students, can further reduce instability in the system. Implementing isolated policies aimed only at reducing the number of students supported by the NIH, however, has limited benefits and can negatively impact the overall levels of scientific output.

In addition, political campaigns that target the doubling of budgets are still commonplace and are an example of policy resistance despite the undesirable outcomes that past initiatives have yielded. This study contributes to the growing body of system dynamics literature that studies how seemingly positive policies might not be as effective in practice, and can instead worsen the conditions of a particular system. These types of models can serve as persuasive tools to influence policy-makers, while allowing for simulation experiments before actual policies are implemented.

Lastly, the dynamics of a particular research workforce and its relationship with public funding, biomedicine and the NIH in this case, could bear similarities across various areas of knowledge. Other public agencies and organizations, such as the NSF, whose funding plays a critical role in the advancement of science, can benefit from these transferrable insights and policy strategies. Future work on the model presented in this paper, and on similar new models, can shed light into additional strategies that government and other players can implement to enhance the behavior of complex systems.

VI. Bibliography

Agres, Ted. "'Looming crisis' from NIH budget." *The Scientist*, March 20, 2007.

Benderly, Beryl Lieff . "Be Careful What You Wish For." *Science Careers From the Journal Science.* July 13, 2007. http://sciencecareers.sciencemag.org/career_development/previous_issues/articles/2007_07_13/caredit_a0700099 (accessed March 18, 2012).

Brainard, Jeffrey. "What the NIH Bought With Double the Money." *The Chronicle of Higher Education* 50, no. 22 (February 2004): A17.

Collins, Francis S. "Fiscal Year 2012 Budget Request." *National Institutes of Health.* May 11, 2011. http://www.nih.gov/about/director/budgetrequest/fy2012budgetrequest.pdf (accessed November 20, 2011).

Couzin, Jennifer, and Greg Miller. "Boom and Bust." *Science* (AAAS) 316 (April 2007): 356-361.

Forrester, Jay Wright. *Industrial Dynamics.* Cambridge: MIT Press, 1961.

Freeman, Richard B. "Supply and Salary Adjustments to the Changing Market for Physicists." *The American Economic Review* (American Economic Association) 65, no. 1 (March 1975): 17-39.

Garrison, Howard H, Susan A Gerbi, and Paul W Kincade. "In an era of scientific opportunity, are there opportunities for biomedical scientists?" *The FASEB Journal.* October 2, 2003. http://www.fasebj.org/content/17/15/2169.full (accessed November 21, 2011).

Ghaffarzadegan, Navid, John Lyneis, and George P Richardson. "How small system dynamics models can help the public policy process." *System Dynamics Review* 27, no. 1 (October 2010): 22-44.

Glenn, Brandon. "Top NIH grant funding by institutions, states for 2010." *MedCity News.* March 7, 2011. http://www.medcitynews.com/2011/03/top-nih-grant-funding-by-institutions-states-for-2010/ (accessed November 2, 2011).

Hibel, Andrew. "The Current State of the Postdoc Experience." *HigherEd Jobs.* http://www.higheredjobs.com/HigherEdCareers/interviews.cfm?ID=184 (accessed December 15, 2011).

Hinck, Robert. "R&D Funding: Obama v. Bush." *Center for Strategic and International Studies.* http://csis.org/blog/rd-funding-obama-v-bush (accessed March 18, 2012).

Kaiser, Jocelyn. "House bill signals the end of NIH's double digit growth." *Science* 300, no. 5628 (June 2003): 2019.

—. *Success Rates Squeezed As Budget Growth Slows.* February 18, 2005. http://sciencecareers.sciencemag.org/career_magazine/previous_issues/articles/2005_02_18/noDOI.14460617739196319071 (accessed 03 21, 2012).

Levin, Yuval. "The New Atlantis." *Reforming NIH: Lessons from a Decade of Missed Opportunities.* 2007. http://www.thenewatlantis.com/publications/reforming-nih (accessed March 18, 2012).

Mack, Connie. "THE BENEFITS OF MEDICAL RESEARCH AND THE ROLE OF THE NIH." *Federation of American Societies for Experimental Biology.* May 2000. http://www.faseb.org/portals/0/pdfs/opa/2008/nih_research_benefits.pdf (accessed December 20, 2011).

Mervis, Jeffrey. "NIH Shrinks, NSF Crawls as Congress Finishes Spending Bills." *Science* 311 (2006): 28.

Monastersky, Richard. "The Real Science Crisis: Bleak Prospects for Young Researchers." *The Chronicle of Higher Education* 54, no. 4 (September 2007): A1.

National Cancer Institute. *Greater Than the Sum: Systems Thinking in Tobacco Control.* Tobacco Control Monograph No. 18, National Institutes of Health, National Cancer Institute., Department of Health and Human Services, Bethesda: NIH Pub. No. 06-6085, 2007.

NIH. "About NIH." *NIH.* December 5, 2011. http://www.nih.gov/about/ (accessed January 8, 2012).

—. "Appropriations History by Institute/Center (1938 to Present)." *NIH Office of Budget.* 2012. http://officeofbudget.od.nih.gov/approp_hist.html (accessed November 2, 2011).

—. "Nobel Laureates." *NIH.* October 5, 2011. http://www.nih.gov/about/almanac/nobel/ (accessed January 12, 2012).

NIH OER. "NIH Office of Extramural Research." *NRSA Training.* July 13, 2007. http://grants.nih.gov/training/q&a.htm (accessed November 2, 2011).

NIH RePORT. "NIH Awards by Location and Organization." *NIH Research Portfolio Online Reporting Tools.* June 24, 2011. http://report.nih.gov/award/organizations.cfm (accessed February 3, 2012).

Pear, Robert. "Government Ready to Boost Spending for Biomedicine." *The New York Times.* January 3, 1998. http://partners.nytimes.com/library/politics/010398clinton-budget.html (accessed January 29, 2012).

Richardson, George P. "Reflections on the foundations of system dynamics." *System Dynamics Review* 27, no. 3 (2011): 219-243.

Ripple Effects Communications Inc. "NIH Request for Information: Future Biomedical Research Workforce." 2012.

Ruiz Bravo, norka. "Scientists in the Pipeline: Creating and Maintaining a Sustainable Workforce." *NIH Division of Program Coordination, Planning, and Strategic Initiatives.* November 8, 2007. http://dpcpsi.nih.gov/council/pdf/CoC-110807-Bravo-ScientistsInPipeline.pdf (accessed March 18, 2012).

Sachs, Frederick. "Is the NIH budget saturated? Why hasn't more funding meant more publications?" *The Scientist.* September 11, 2007. http://classic.the-scientist.com/news/display/53580/ (accessed March 18, 2012).

Simon, Herbert A. *Models of Man, Social and Rational: Mathematical Essays on Rational Human Behavior in a Social Setting.* New York: John Wiley and Sons, 1957.

Smith, Pamela W. "The National Institutes of Health (NIH): Organization, Funding, and Congressional Issue." *NIH.* October 19, 2006. http://www.nih.gov/about/director/crsrept.pdf (accessed March 18, 2012).

Sterman, John D. *Business Dynamics.* Boston: Irwin McGraw-HIll, 2000.

Sturtevant, Daniel J. "America Disrupted: Dynamics of the Technical Capability Crisis." Master's Thesis, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, 2008.

Teitelbaum, Michael S. "Structural Disequilibria in Biomedical Research." *Science* (AAAS) 321 (August 2008).

Timmer, John. "How doubling the NIH's budget created a funding crisis." *Ars Technica.* 2008. http://arstechnica.com/science/news/2007/04/how-doubling-the-nihs-budget-created-a-funding-crisis.ars (accessed March 18, 2012).

University of California - Davis Health System. "Experts advocate for new approaches to biomedical research." *Science Daily.* . September 28, 2011. http://www.sciencedaily.com /releases/2011/09/110928142446.htm (accessed March 18, 2012).