The Long-Term Impact of University Budget Cuts: A Mathematical Model

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Abstract

Policymakers acknowledge the regional benefits of the university, yet cut higher education budgets. Incorporating the theory of diffusion of innovation, we develop a mathematical model to explore the long-term effects of university budget cuts. Simulations indicate that the full impact of budget modifications may not be realized for several decades.

Key words: mathematical university model, diffusion of innovation, higher education, tertiary education, budget cuts

[1] L. G. de Pillis was supported in part by the U.S. Department of Energy under Contract W-31-109-ENG-38, and in part by a Harvey Mudd College Faculty Research Grant.
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1 Recent Budget Cuts to Higher Education

Since the early 1970s, the University of Hawaii has suffered ongoing budget cuts and freezes. Frequently, personnel have been dismissed and not replaced, and services have been curtailed [1]. The current governor of Hawaii, Ben Cayetano, visited Silicon Valley in 1999. On March 3, 1999, the Honolulu Star Bulletin reported: "On a trip to California's Silicon Valley last week, the governor said he learned that tax incentives are at the bottom of the list when it comes to attracting high-tech companies ... 'The education system and having a good university is important, ... more important than tax incentives,' he said" [2]. Yet, as of April 2000, the University of Hawaii continues to work with an attenuated budget.

Hawaii's situation is not unique. Policymakers nationwide acknowledge that the presence of a university carries economic and social benefits, yet policy decisions often reflect the assumption that university budgets can be cut without eventually paying a price.

Colleges and universities in the United States are attempting to educate more students with relatively fewer resources than ever before. If current enrollment trends continue, and tuition increases at the rate of inflation, it is estimated that by the year 2015 the the nation's colleges and universities will have an operating deficit of $38 billion in 1995 dollars [3].

When state budgets are tight or political winds shift, legislators' first response may be to cut funds to higher education. Even in times of economic prosperity, with many factions competing for state funding, higher education tends to be a tempting target for cuts. For example, in California, higher education has traditionally constituted nearly ten percent of the state budget, but in 1996-1997, the California state budget appropriated more money for corrections (9.4%) than for higher education (8.7%). Since 1984, the California Department of Corrections has added 25,864 employees, while reducing the number of higher education employees by 8,082 [4,5].

In an attempt to answer the demand for increased accountability in the face of shrinking higher education budgets, even prestigious institutions have resorted to justifying their existence through regional impact studies, which usually demonstrate that keeping the university in the area is more economically beneficial to the region than shutting it down [6]. These studies do not address the more relevant issue of attenuated budgets, however.

This is unfortunate, because a healthy, adequately funded system of higher education confers many benefits upon its recipients and upon society as a whole. We argue that draining resources from state-funded colleges and universities will eventually diminish the positive regional effects of these institutions. It is not sufficient simply to have a college or university in a region; an institution starved of resources will eventually cease to do those things that invigorate the local economy.

To create a mathematical model that will enhance our understanding of the long-term effects of persistent university budget cuts, we begin with a brief review of relevant literature in higher education. In section 2 we present an overview of the published research that supports the assertion that an active university fosters regional economic activity. In section 3 we describe some of the factors that influence university productivity levels. In section 4 we briefly describe the methodology and limitations of existing university economic impact studies.

We then address some of these limitations by building upon the theory of diffusion of innovation to develop a mathematical model describing the dynamics of the university economy. In section 5 we translate the evidence from the literature into a relatively simple deterministic mathematical model, incorporating the process by which university budget levels affect productivity and how productivity in turn affects regional industrial activity. By employing a system of ordinary differential equations, we demonstrate through numerical simulations some possible mechanisms by which university budget cuts may lead to attenuation of benefit over time.

2 Benefits of Education

Education has long been recognized as providing benefits to the individuals being educated and to overall social and economic health. By 1776, Adam Smith had come to devote a good deal of thought to the role of education in society, and concluded that money spent on education was "no doubt, beneficial to the whole society" [7,8]. A nineteenth-century economics textbook stated, "We may then conclude that the wisdom of expending public and private funds on education is not to be measured by its direct fruits alone. It will be profitable as a mere investment, to give the masses of people much greater opportunities than they can generally avail themselves of" [9, p. 216]

In Europe, universities have been established for the express purpose of boosting regional development. Examples are the University of Twente near the industrial area of Twente, the University of Limburg in Maastricht, universities in Trier, Germany and in Calabria, Italy, and the universities of Umeå and Luleå in Sweden [7].

2.1 Empirical Evidence for the Positive Influence of Education

Improving the educational system in a country or region has been shown to confer various economic and social benefits. Education benefits the individual recipients throughout their life and bestows benefits upon society in general [10, p. 68].

Education is recognized as a crucial part of economic development [11,12,13] especially in developing countries [14,15]. Research indicates that education is an important part of moving an economy from agriculture based to industry based [16]. According to Chatterji, "An economy experiencing growth has shifts in its employment characteristics, with a move from a large agricultural sector into a more industrialized pattern and then into a services oriented sector. This experience can only begin when the population has a basic level of education" [17, p. 352].

For example, in a study comparing thirty Chinese provinces, provinces with higher literacy rates and higher average years of schooling experienced a faster decrease in the percentage of the population employed in agriculture than did provinces with lower literacy rates and lower average years of schooling. In this study, the initial year's education variables were used in the analysis, so it is likely that the causality runs from education to economic development. Provinces with the higher average years of schooling in the initial year demonstrated higher growth rates of real per capita GDP in the subsequent year [10].

Several studies, including [18] and [19], indicate that the cultivation of human capital is an important contributor to economic growth. Human capital has helped to explain sustained economic growth in East Asian nations [20,21]. In these studies, economic models using only physical investment variables have performed poorly in explaining economic growth, but the same models have performed well when human capital was included [22].

In a recent study, Fedderke and Klitgaard concluded: "That investment in human capital, such as education, yields long-term economic growth [18,19] was borne out in a recent multi-country meta-analysis, which found a positive correlation between education measures and long-run economic growth" [23]. Reviews of the literature on rates of return to education indicate that both private and social rates of return to education are positive [24,25,26]

2.2 The Benefits of University-Level Education

Not only is education in general beneficial to regional development, but tertiary education in particular has been found to be an important driver of economic growth. Public investment in university-level education and research has been shown consistently to pay dividends in economic growth and enhanced productivity [27,28,29]. University-level education has been found to be more significant in this regard than primary or secondary education, as was found in a recent analysis of 81 countries: in every regression specification where both secondary and tertiary education were used, tertiary education was more significant than secondary education. The author concluded, "In policy terms our results suggest that tertiary education deserves more attention than has previously been the case" [17, p. 354]. The social benefit rate of return to higher education has been estimated empirically at 12 percent (private) and 9 percent (social) for an advanced economy [30, p. 87]. Similar research in the Netherlands also shows positive, albeit slightly lower figures, with a private rate of return of 5.6 to 7.3 percent for university graduates [31]. Completing a bachelor's degree in Australia yields a private rate of return of 9.6 percent for males and 12.6 percent for females [32]. Social rates of return as high as 15 percent have been found in Australia [33] and New Zealand [34].

One can argue that the high rates of return to tertiary education can be accounted for by selection bias: the most able citizens of a region are chosen to receive a college degree, and their activities would have benefited the economic life of the region with or without a college education. In studies that have attempted to investigate this possibility, the effects of selection bias have been shown to be small. Research on selection bias has used various methods such as path analysis to account for interaction effects [35] and identical twin data [36,37]. Miller, Mulvey, and Martin [37] conclude that both their work and that of Ashenfelter and Krueger [36] indicate "little evidence of upward bias in the typical OLS [ordinary least squares] estimate of returns to education" [37, p. 597].

2.3 Mechanism by which University-Level Education Benefits the Economy

To date, no comprehensive structural model links social institutions and economic growth [23], but individual studies indicate that the presence of an active, effective university benefits the community in several ways.

2.3.1 Enlarging the Supply of Human Capital

Human capital is "one of the major factors of enhancing growth" [17, p. 352], [38]. The human capital model holds that educational institutions provide students with skills and knowledge that have value. Students sacrifice time and current income in order to obtain greater rewards in the future [39,13]. In the narrowest interpretation of this model, the knowledge and skills acquired in a formal education bring about higher earnings. This definition is straightforward to work with because earnings are quantifiable, but the benefits of education can extend further. A capacity to appreciate literature, for example, can enhance the quality of life in a nonmonetary way [22].

Consistent with the broader interpretation of human capital theory, there is evidence that education confers other nonmonetary benefits as well. More educated individuals have better health knowledge and better health status, even after controlling for such variables as family income [40,41]. Other cited benefits include transmission of cultural values [42], more intelligent voting behavior [43], and reduced predisposition to criminal behavior [44]. Universities not only produce knowledge but also add an "attractiveness value" to the region and confer both short-term and long-term benefits by virtue of hiring staff immediately and educating students who will enjoy higher earnings later [29, p. 1568].

The presence of skilled, trained workers, such as university graduates, appears to raise regional productivity overall. The presence of a university increases productivity overall by raising the level of technology that is used [45,29]. An individual worker tends to be more productive when working in an environment peopled by other highly skilled workers than when working in a low-skill environment [46].

2.3.2 Fostering Specific Skills, Technical Knowledge, and Commercially Viable Research

Universities impart technical skills, work habits, and certain social skills. The research that takes place at a university can encourage investments in a region, which then drive economic growth [17,7,47]. In Sweden, regional production has been found to be a function of regional R&D capacity and the number of full professors [48]. In the United States, universities have been found to promote regional growth specifically through electronics, engineering, and instrument industries [49].

By socializing students into accepted business norms, a college education may strengthen social ties and enable social and financial transactions to proceed smoothly [50,51]. Students learn to maximize the use of their intellectual abilities, allowing them to be innovative and creative in business [17,46].

The university can interact with the region in various ways, including "via graduates employed by private firms, reported research results and various kinds of consultancy" [7, p. 184].

2.3.3 Promoting Economic Activity

Universities have been likened to "a business complex, running specialized research centres and even hospitals, housing and residential accommodation, sports, catering and cultural facilities and sometimes associated with commercial ventures like a science or business park" [29, p. 1565]. A large university can occupy thousands of workers and millions of dollars. Simply because of their size and presence, universities are bound to have some positive effect on economic development [29]. The presence of local and out-of-state students further enhances the university's economic impact [52].

2.4 Necessary Condition for University Benefits to Be Realized

Merely having a university in an area does not guarantee a fixed amount of benefit to the community. Certain factors affect the magnitude of benefit that the university confers.

2.4.1 Adequate Primary and Secondary Educational Infrastructure

In underdeveloped countries that lack primary and secondary education, an expansion of the university system would not necessarily provide measurable regional benefits until the lower levels of education have been brought up to adequate standards [53].

2.4.2 An Existing Local Economy in Reasonable Health

Some local job opportunities for graduates are needed. If those are not available, the graduates will leave, taking their enhanced social capital with them. According to Felsenstein, "The existence of a university-generated, skilled-labour pool can attract existing firms from other places and can also lead to an increase in local new firm formation rates. However ... this total effect will only be felt if some of the students attracted to the university stay on in the area after their studies" [29, p. 1568].

The region should offer something for university students and employees to spend their money on. "The narrower the economic base of the area, the more likely the expenditure impacts are to flow out", notes Felsenstein. "This is the dilemma of the local economic development contribution of the university in a small town or open economy. Burdens are felt locally, while benefits are perceived as diffusing nationally" [29, p. 1574].

2.4.3 Good Reputation Outside the Region

The more a university can attract nonlocal students (as well as local students), the more benefit it will have upon the region. Felsenstein explains: "The more the university functions akin to an 'export-base' sector, internalising these linkages within the local area, attracting external funding and non-local students and then selling the final product outside the area, the greater will be its local economic impact" [29, p. 1567].

A healthy regional economy and a successful university are mutually reinforcing. In order to get this virtuous cycle in motion, the university requires faculty that will enhance the university's reputation through effectively fulfilling the mission of the institution, whether it be research, teaching, or something else. Through faculty activity supported by effective administration, the university's reputation is enhanced. The coordinated, cooperative actions of faculty and of administrative and support staff are crucial. An enhanced reputation built upon effective fulfillment of the institution's mission will attract students from outside the region.

3 Factors Motivating University Employees to Be Productive

Research suggests that it difficult or impossible to motivate employees who do not wish to be motivated or to bribe employees into being enthusiastic about their work. However, it is dismayingly easy to demotivate employees. For the sake of our model we focus on three main factors that drive motivation and demotivation: adequate institutional support, availability of resources, and the actions of colleagues.

3.1 Adequate Institutional Support

Herzberg's classic motivation-hygiene theory suggests that employees are most motivated by intangible factors such as achievement, enjoyment of the work itself, recognition, and responsibility [54]. This may help to explain the apparently irrational career choices of university faculty, who invest a great deal of time, effort, money, and opportunity cost in building careers that bestow relatively modest financial returns.

This does not mean, however, that university employees do not need to be compensated financially. In Herzberg's model, "satisfaction" and "dissatisfaction" are on two different continua. The opposite of "satisfaction" is "no satisfaction," and the opposite of "dissatisfaction" is "no dissatisfaction." High pay, for example, cannot create satisfaction where none existed before, but the perception of unfairly low pay can create dissatisfaction. Employees can be demotivated very effectively by perceptions of insufficient pay, inequitable work assignments, and inefficient organizational procedures [54,55,56]. Herzberg's dissatisfiers, or "hygiene factors," include insufficient pay raises, inadequate administrative support, and poorly maintained physical facilities. High on the list of items that are commonly forfeited when budgets are cut are precisely those things—salary increases, administrative support, regular facilities maintenance, and so forth—that, when sacrificed, lead to the presence of dissatisfiers.

A recent study of midlevel administrators indicated that morale was determined by administrators' perceptions that they were treated fairly, that they and their opinions were valued, and that their work was meaningful. At the individual level, perceptions of worklife had a direct impact on midlevel administrators' morale. Worklife perceptions accounted for about 18% of the within-group variance in morale, and morale in turn accounted for about 14% of the within-group variance in intent to leave [57].

Similarly, university faculty are also motivated by achievement, responsibility, recognition, status, competency, personal growth, and satisfaction from the work itself. If these needs are not fulfilled, then motivation will decline, regardless of pay level or tenure [58]. Not only do motivation and satisfaction decline in the absence of institutional support, but continued attenuation of resources can lead to the presence of dissatisfiers. As budgets decline, physical facilities deteriorate, and politics loom large as increasingly desperate factions compete for ever-scarcer resources. An increased emphasis on frugality often leads to elaborate tracking and documentation of every penny spent, and consequently to Herzberg's leading workplace dissatisfier: inefficient and frustrating organizational rules [55]. It seems reasonable to predict that widespread demotivation, followed by a decrease in effective fulfillment of the institution's mission, will follow.

3.2 Availability of Resources

Apart from the question of demotivation, the lack of necessary resources will negatively affect the ability of university employees to perform their jobs in order to further the university's mission. The lack of adequate resources will constrain performance regardless of motivation or intentions [59]. For example, a professor who no longer has a student helper will need to give up class preparation or research time in order to perform the grading or lab work that the student helper used to cover.

Research on downsizing in organizations has recently focused on downsizing's negative repercussions and failure to live up to its initial promise. Only around 25% of firms that downsized have achieved improvements in productivity, cash flow, or shareholder return on investment [60]. Downsizing appears to have unintended negative consequences for individuals and organizations [61,62,63,64]. Downsizing has been found to result in feelings of job insecurity, anger, job stress, decreased loyalty and organizational commitment, lowered motivation and productivity, and increased resistance to change [65,66,67,64]

While most of the downsizing research has been done in business organizations and not universities, it seems reasonable to assume that the consequences of downsizing within the university may be similar.

3.3 Actions of Colleagues

In academia, as in many professions, the opinion of peers and norms of the professional group are more important than formal sanctions and rewards in directing behavior. Peer group standards and the enforcement of those standards by subtle peer pressure constitute the primary means of ensuring compliance to expectations, whether those expectations are for high or low productivity [58]. If demotivation leads to changes in effort expended by some individuals, group norms may shift and discourage the output of extra effort by faculty [68].

4 Methodology Commonly Used in University Economic Impact Research

Three approaches have been used in studying the university and its effect on economic development:

1. Correlating the concentration of high-tech activity with various location factors such as a university in the area, as well as wage rates, amenity levels, and so forth. These studies show the influence of the university to be weakly positive.
2. Examining university-induced growth. These studies usually show the university to have a positive effect.

3. Examining local impact of one specific institution, and accounting for direct impacts of such things as employment, income, and sales. This research follows the American Council on Education report that set out a standardized research framework for these studies [69,29]

The usual way to perform an economic impact study is to use the third method, manufacturing a scenario in which an existing university ceases to exist, and examining the differences between the university and the no-university scenarios. This approach is illustrated in one definition of economic impact: "We define economic impact as the difference between existing economic activity in a region given the presence of the institution and the level that would have been present if the institution did not exist" [52, p. 2].

As research on regional economic development has accumulated, and at the same time politicians and community groups have demanded accountability from their local universities, studies of the impact of the university on the regional economy have proliferated. Analysis of rates of return to education have been performed in many countries in an effort to understand and accelerate the process of development [70]. In the United States, economic impact studies increased in number and prominence beginning in the 1960s; by 1976, there were over seventy economic impact studies concerning colleges and universities in the United States [71,7]. Today, economic impact studies are commonly used as public relations tools for colleges and universities [72].

Although the abundance of economic impact studies has made substantial contributions toward understanding the regional benefits of the presence of universities, this form of study does suffer from some limitations.

4.1 Impact Study Limitation: Lack of Empirical Data

Little empirical data are available for use in investigating the internal functioning of a university. Because of this persistent lack of empirical data in higher education, researchers have made contributions to this area by instead appropriately adapting relevant findings from research in other professions, such as medicine. For example, the work of Bess [58] addresses the problem of financial nonprofessionals placing constraints on the activities of professionals, based not on professional but solely on financial criteria. In particular, Bess was interested in examining the motivational effects of tenure within the university, but because of lack of findings particular to this setting, findings were adapted from the medical profession [73,74,75,76].

4.2 Impact Study Limitation: Disentangling Causality

In a recent study on expenditures and growth, Kelly points out the problem of identifying causality: "Simultaneity is a problem which plagues this literature . . . one might argue that virtually all of the other independent variables [in the study of public expenditures and growth] are products rather than causes of growth" [53, p. 65]. For example, budget cuts may be made to a state university system as a legislative response to economic troubles in the state overall. The university's decline can then be observed to correlate with that of the region, but it becomes difficult to determine the proportion of regional decline that is in some way attributable to resource shortages within the university.

4.3 Impact Study Limitation: Short Time Horizon

The effects of the university on a region are both long-term and short-term. Felsenstein states, "The local income effect associated with an increase of staff at a university is more or less immediate, whereas the income effects associated with producing know-how or training skilled labour are spread out thinly over the course of the lifetime of these resources" [29, p. 1568]. Long-term effects, unfortunately, are difficult to measure, since the complete rate of return to education can only be assessed at the end of an individual's lifetime. Some researchers have addressed this by using long-term census data [22].

4.4 Impact Study Limitation: Binary Nature

Most important, these economic impact studies tend to be binary in essence, comparing the impact of an existing institution to what the effect might be if the institution were to be completely removed. Beck et al. comment on the limitations of such studies: "An economic impact study, by its very nature, must always be a comparative analysis. The current state of the world is usually obvious and easy to describe. The alternative state of the world is too frequently left implicit for the reader to guess, left ill-defined so as to call into question the value of the analysis, or manipulated in an unrealistic fashion to bloat the impact estimate for publicity's sake. None of these practices serve the profession, the analysis, or the public well" [52, p. 13]. In other words, the long-term continuum effect of slowly starving a university of funding and support is not, and cannot be, accounted for in such studies.

5 The Mathematical Model

Through the use of simultaneous continuous differential equations, we seek to address some of the limitations of existing research. In this section, we describe a mathematical model to simulate the effects of budget cuts upon the various interactions within the university organization: budget levels upon faculty, faculty upon faculty, students upon students, and cross-population interactions. Ultimately, we examine the effect of faculty and students upon industry.

The use of a mathematical model of this nature allows us to simulate continuous, as opposed to binary, phenomena and to incorporate the simultaneous effects of mutually interacting populations. Additionally, simulations can be carried out over long time frames.

The model we present is intended to serve as a framework for analysis. Into this framework must be placed the coefficients and parameter values that are tailored to reflect the specific situation under study. Unfortunately, as with other studies in the literature, the problems of lack of empirical data and of quantifying intangible phenomena persist. However, when possible, relevant observations in the literature are translated into mathematical model elements.

5.1 Mathematical Model - Overview

The kernel of our model is built upon mechanisms that are similar to those used to describe the diffusion of technology and innovation. Mathematical models of diffusion of innovation were introduced by Mansfield [77] in the context of studying how rapidly the use of a number of innovations spread from enterprise to enterprise in several separate industries. For a simple development of the mathematical model of diffusion of innovation, see, for example, Braun's text [78, pp. 37-43].

Diffusion of innovation models can be appropriately used to describe any situation in which the development, implementation, and dissemination of new ideas, behaviors, methods, or products in a business, an organization, or in society as a whole are of interest. For example, Strang and Soule [79] examine the factors that motivate individuals to adopt certain behaviors and how the theory of diffusion of innovation applies to the pattern of individual decision making. In the model we develop, we think of "productivity" or "success" as a behavior or quality that can be diffused throughout the university organization. The model we create is then built upon a mathematical description of the diffusion of productivity or success and on factors that can either accelerate or dampen the rates at which such diffusion takes place.

The definition of "productivity", or "success", is one that varies in accordance with the particular requirements and standards of a given institution. We define productivity and success in relative terms, as actions that fulfill the mission of the institution. For example, productivity in a faculty member could be quantified by accounting for teaching evaluation scores, number of papers published, number of talks given, or number of external grants received in a given year. Productivity, or success, in a student might be quantified by grade point average, standardized test scores, or successful fulfillment of graduation requirements. In the mathematical model presented here, we allow a member of a population to be categorized either as productive or nonproductive. In future refinements of this model, we plan to allow for the possibility of multiple levels of productivity and success within a population.

Evidence from the literature discussed in sections 2 and 3 leads us to build into our model the following assumptions regarding population interactions and causality:

- *The actions of peers affect individual behavior.*

  As discussed in section 3.3, the literature on professions indicates that the enforcement of peer group standards constitutes the primary means of ensuring compliance among professionals to expectations of productivity. We call this the "peer pressure factor" and account for it in our model by allowing the presence of productive faculty to stimulate further productive behavior among faculty. We extend the application of the peer pressure factor to the population of students as well, allowing the presence of successful students to foster even more success in the student population. The mechanism by which productivity and success are diffused throughout a population will be described mathematically by a diffusion of innovation term.
- *Adequate institutional support affects productivity levels.*

  Motivation-hygiene and downsizing studies, such as those discussed in section 3, indicate that decreased budget levels often lead to decreased levels of productivity within an organization, through restriction of resources, decimation of work groups, and demoralization of individuals. In contrast, the works cited in section 2 point to the positive correlation between public investment in university-level education and the benefits of tertiary education, including economic growth with enhanced productivity. We find it, therefore, reasonable to assume for the sake of this model that adequate levels of well-spent funds will encourage higher levels of productivity in the professor population. We emphasize that we do assume funds are being well spent by some measure, and not simply being absorbed into nonproductive endeavors. Precisely how funds should be apportioned within a university budget in order to encourage maximal productivity is a separate question, which we plan to address in a future work.

- *Faculty affect funding levels.*

  One outgrowth of the kinds of endeavors that are commonly considered productive is the procurement of external grant funding. Since this is a readily quantifiable measure of productivity, we choose this to be a feature associated with productive behavior in this particular model. We are not specifying the ability to bring in grant dollars as a cut-off measure of productivity. We are simply allowing for the assumption that *on average* the individuals within the class of productive professors will bring in some fixed number of external grant dollars per professor per year. In particular, some productive professors may bring in zero dollars while others bring in twice the average.

- *Availability of resources affects productivity levels.*

  In this simple model, we consider a pool of good students to be a resource for professors. Simultaneously, active professors are a major resource for students. We reflect the need for availability of resources, therefore, not only by incorporating the beneficial effects of increased budget levels on productivity but also by allowing the populations of students and professors to simultaneously affect each other.

- *The university fosters regional industrial growth.*

  As outlined in sections 2.2 and 2.3, a substantial body of evidence indicates that a university can have a positive economic regional influence and that an increase in the regional level of industry is one economic indicator. We therefore reflect this dynamic in our model. We incorporate the beneficial economic effects of a university by allowing the presence of productive professors and successful students, in particular, to positively affect the number of industrial positions in the region.

We build up our model in stages. We attempt to adhere to the philosophy that a mathematical model should be as simple as possible, incorporating only those elements that are assumed to impact the model behavior significantly, and then adding complexity only when deemed necessary. We start with a single population of professors, then add students, and finally industry to complete the model.

5.1.1 One Population: Professors

We begin by developing a very simple model to describe the change over time in the size of a single population: the population of productive professors at a university. The influencing factors in this case will be the presence of other productive faculty, as well as external government and grant funding.

5.1.2 Two Populations: Professors and Students

After completing the development of the model of the diffusion of productivity among university professors, we add a second population to the model: students. Incorporating the peer pressure effect for students, we include a logistic diffusion term to describe the development in time of the successful student population. We additionally incorporate the assumption that the presence of good students has a positive effect on the population of productive professors, while the lack of good students will have a negative effect. Simultaneously, the population of good students will be positively affected by the presence of productive professors, and negatively impacted by the lack of productive faculty. We choose not to incorporate effects of tuition levels, assuming for the sake of this simple model that income from tuition and fees are approximately balanced by expenditures per student. The direct financial impact of the student population will be incorporated in future model extensions.

5.1.3 Three Populations: Professors, Students, and Industry

Finally, we include a third population in the model: the number of industry-based positions in the region. Although an already active economy can have a positive effect on the university, we choose for now to assume that the number of industry jobs in the region will not directly affect the level of productivity or success in the professor or student populations. Further complexity can certainly be added to the model to allow for this effect. However, we do allow the number of industry-based positions in the region to be directly affected by the population of qualified students and active faculty in the area. Additionally, in keeping with the theory of diffusion of innovation, we allow industry to affect industry in a logistic manner.

A graphical representation of the simultaneous three-population model dependencies is given in Figure 1.

[Fig. 1 about here.]

5.2 Stage 1: The Professor Model - Equations

In this section we introduce the terms needed for the simplest mathematical model, tracking only the interaction between external funding and productive professors.

- $P(t)$ = total number of "productive" professors at time t. At this stage we assume that a professor is either productive or not. We have not incorporated degrees of productivity, and we have not specified the precise measure of productivity. As discussed above, any quantifiable measure of productivity consistent with the mission of the institution can be used.
- P_T = total number of professors at the university. We assume that we are not trying to grow the total number of professors at this point (although in a later model we may wish to allow for such growth).
- I_P = average income, or number of grant dollars, that a productive professor is able to procure in a year. Again, productive behavior is defined as actions that fulfill the mission of the university.
- E_P = average expenditure, or amount of money, needed to provide basic support one full-time professor for one year.
- E_T = total expenditures needed to maintain the current faculty population faculty for one year. In this case, $E_T = P_T E_P$.
- $I_E(t)$ = total income from external grants at time t. Since we assume that each productive faculty member is able to produce, on average, I_P external grant dollars, we have $I_E(t) = I_P P(t)$.
- O_T = fraction of overhead taken out of the total amount of faculty grants and claimed by the university administration. We have $0 \leq O_T \leq 1$.
- α = fraction of overhead, O_T, reinvested by the administration to support productive activities in the faculty population. We have $0 \leq \alpha \leq 1$.
- $F(t)$ = amount of external grant funding used to support productive activ-

ities in the professor population. Here we let $F(t) = (1 - O_T + \alpha O_T)\, I_E(t)$. The term $I_E(t) = I_P P(t)$ represents the total number of external grant dollars available at time t, and the coefficient $(1 - O_T + \alpha O_T)$ represents the fraction of those grant dollars that are used directly to support productive endeavors.

- I_G = total income to the university from government funding per year.

The change over time in the size of the population of productive professors can be thought of as happening in one of two ways. Either a single individual can leave the nonproductive population and become part of the productive population, or a nonproductive individual may leave the system altogether and be replaced by a new productive individual. For example, a nonproductive professor may become productive because he is now receiving sufficient funds to support his research, or because she is inspired to productivity by the active researchers who surround her. Alternatively, a nonproductive professor may simply leave the university through retirement or failure to achieve tenure and then be replaced by a productive professor who is attracted to the university by the presence of other active researchers as well as the availability of substantial research support. Mathematically, both occurrences can be described in the same way: when one population loses an individual, the complementary population gains an individual. Of course, this is allowed because of the assumption of constant total population size. Future model refinements will allow for fluctuations in total population size, and the mathematical description will become more complicated.

How the productive professor population changes in time is described as follows: Assume that the number of professors who convert from being nonproductive to being productive at any instance in time is directly proportional to the fraction of professors P/P_T who are already productive, and the population of professors $P_T - P$ who remain nonproductive. Then the differential equation describing the diffusion of productivity among professors can take the following form:

$$\frac{dP}{dt} = c\left(\frac{P}{P_T}\right)(P_T - P). \tag{1}$$

Through coefficient c we incorporate the effect of funds that are made available to encourage productive activity. Equation (1) has the form of a basic mathematical diffusion of innovation model. Diffusion of innovation models have solutions that are logistic in nature. This means that the process of innovation adoption accelerates to a point and then decelerates as the innovation begins to saturate the community.

We let c have the form $c = c_0\left(c_1(I_G - E_T) + c_2F\right)/E_P$. This says that P will be positively affected by any amount of government funding I_G that exceeds the minimum necessary expenditures, E_T, as well as by the availability of external grant funds that are being put toward the development and maintenance of productive professors. On the other hand, if I_G drops below E_T, this will negatively impact the growth of P. The coefficients c_0, c_1, and c_2 are scaling coefficients. The entire coefficient c is scaled by $1/E_P$, in order to convert the units from dollar amounts to units of full-time professors. The differential equation describing $P(t)$ is then given by

$$\frac{dP}{dt} = c_0\frac{(c_1(I_G - E_T) + c_2F)}{E_P}\left(\frac{P}{P_T}\right)(P_T - P)\,. \tag{2}$$

5.3 Stage 1: The Professor Model - Numerics

Recall that there is a lack of relevant empirical data in the literature from which we can derive precise model parameters. In fact, according to Fedderke and Klitgaard [23], no comprehensive structural model links social institutions and economic growth. In previous economic impact studies, the contributions of universities to human capital and economic development have been acknowledged but have not been quantified [52].

In the face of this unfortunate absence of quantitative data, we are compelled to simulate the evolution of our system within a hypothetical university setting. The mathematical model is simply a framework for analysis, into which one must insert the specific parameter values unique to the particular institution being modeled. Therefore, for our hypothetical institution we choose a set of numerical parameter values that make intuitive sense and that give rise to natural results. Experimentation indicates that incorporation of different parameter sets allows the fundamental qualitative behavior of the model to remain intact, while quantitative outcomes will vary. That is, the trends implied by the computational results will continue to follow logistic paths in all simulations, but exact numerical quantities and the speed with which those quantities change over time will differ.

Some behaviors and outcomes are best observed with longer time scales. Quiggen [22] makes the claim that if the rate-of-return approach is to be used appropriately in assessing the output of a school system, then it is necessary to make use of long-term census data. Felsenstein [29] also asserts that the effects associated with producing know-how are spread out over the course of a lifetime. In light of this, we run our simulation over a fifty-year time interval, which should enable us to observe certain long-term trends.

We observe the evolution of $P(t)$ in our single-population model with the following parameter values:

- $P_T = 300$
- $I_P = \$200,000$
- $E_P = \$100,100$
- $O_T = 0.25$
- $\alpha = 0.1$

For this set of simulations, we allow the initial population of productive professors to be 10, that is,

$$P(0) = 10. \tag{3}$$

This is just over 3% of the entire professor population.

In our simulations, we have chosen the initial values for the populations we track to be relatively small. These allow us to demonstrate that, according to this model, simply feeding and maintaining a university, even one with a relatively unimpressive profile, can eventually produce positive results, albeit over several decades.

We assume that dollar amounts are implicitly adjusted for inflation and therefore do not include explicit terms to account for possible changes in the value of the dollar.

Equation (2) is solved numerically through Matlab 5.3 using a variable-order stiff differential equations solver based on the Klopfenstein-Shampine family of numerical differentiation formulas of orders one through five [80].

5.4 Stage 1: The Professor Model - Results

In this section we present numerical solutions of Equation (2). We examine three cases:

1. Maintaining the same levels (relative to inflation) of government funding over the years.
2. Decreasing government funding by 5% per year (relative to inflation).
3. Increasing government funding by 5% per year (relative to inflation).

In each case we modify only the parameter that affects the level of government funding. All other parameters remain the same.

Case 1: Maintaining Government Funding. The effects of maintaining steady funding to the university are shown in Figure 2. The top graph shows the percentage of productive professors from year to year, while to bottom graph plots the raw numbers. We see that the productive professor population is evenly maintained over a fifty-year time span and, in fact, enjoys a very slight increase. As long as government funding is maintained, the population of productive professors will go from being a little more than 3% of the total population to being a little more than 4% of that population in fifty years.

[Fig. 2 about here.]

Case 2: Decreasing Government Funding. The numerical solution to Equation (2) when funding is steadily cut each year is shown in Figure 3. We see from these plots that with the particular parameter set we have chosen, the effect of steadily cutting the university budget each year is that within ten years the productive professor population is reduced by more than 50%, and within about twenty years the productive population is effectively annihilated and never recovers.

[Fig. 3 about here.]

Case 3: Increasing Government Funding. When government funding is steadily increased each year, the effect on the productive professor population is dramatic. In Figure 4 we see a slight but steady increase in the population over the first ten years, after which the increase in productivity accelerates, and by year twenty, the entire population of potentially productive professors has in fact become productive. That population is then maintained over the remaining years.

[Fig. 4 about here.]

5.5 Stage 2: The Professor-Student Model - Equations

We are now ready to add a population of students to our model. We again assume that there is a fixed total student population and that there is a subset of that student population that can be considered successful by some quantitative measure. We introduce the new variable $S(t)$, which represents the number of successful students enrolled at the university at time t. We let S_T represent the fixed total student population.

We first account for the impact the student population will have on the professor population. As discussed earlier, the lack of resources constrains performance, whereas the presence of adequate levels of resources allows for productive functioning. Good students can be considered a positive resource for professors. To reflect the positive impact of the presence of successful students on the population of productive professors, as well as the corresponding negative impact that poor students have on the productive professor population, we include the terms

$$c_3 S - c_4(S_T - S) \tag{4}$$

in our equation for $P(t)$. Parameters c_3 and c_4 are positive scaling factors. An example of a way in which the positive student effect on the professor population might evidence itself is in the availability of a qualified pool of student research and teaching assistants. Poor students could negatively affect professor productivity in that poor students may slow down the progress of a course, consume institutional resources by filing grievances over poor grades, and in sufficient numbers require the addition of remedial courses to the university curriculum.

The differential equation for $P(t)$ then becomes

$$\frac{dP}{dt} = c_0 \left(\frac{(c_1(I_G - E_T) + c_2 F)}{E_P} + c_3 S - c_4 (S_T - S) \right) \left(\frac{P}{P_T} \right) (P_T - P) \,. \quad (5)$$

We also need an equation describing how $S(t)$ changes over time. It is reasonable to assume that the number of students who convert from being unsuccessful to being successful is proportional to the number of successful and unsuccessful students already at the university. This follows the diffusion of productivity model upon which the behavior of the professor population is also based. The conversion from unsuccessful to successful can be considered to take place, for example, when an unsuccessful student is inspired and assisted by surrounding successful students and is thereby converted to being successful. It could also happen when an unsuccessful student leaves the university, and a successful student, attracted by the good reputation of the institution, is admitted. The differential equation describing $S(t)$ then has the form

$$\frac{dS}{dt} = d \left(\frac{S}{S_T} \right) (S_T - S) \,, \quad (6)$$

where d is a proportionality coefficient. To determine the form of d, we make some assumptions about what encourages the growth of the proportion of successful students in the population.

Through coefficient d, we allow for a mechanism by which the presence of productive faculty will positively influence the population of successful students. For example, we might assume that a successful student is attracted to the university by its reputation and that the university's reputation is directly linked to the productivity of its faculty. We might also assume that a student who is already enrolled and who has the potential to become successful can be influenced to success by active faculty, whereas disengaged faculty can even drive a successful student toward becoming unsuccessful. Therefore, we allow that the presence of productive faculty will positively affect the population of successful students, whereas the lack of productive faculty will have a negative impact on the student population. In our equation, then, it is natural to let d have the form $d_0(d_1 P - d_2(P_T - P))$, where d_0, d_1, and d_2 are positive scaling parameters. The change in time of the population $S(t)$ is described by

$$\frac{dS}{dt} = d_0 \left(d_1 P - d_2(P_T - P)\right) \left(\frac{S}{S_T}\right) \left(S_T - S\right). \tag{7}$$

5.6 Stage 2: The Professor-Student Model - Numerics

The numerical values outlined in section 5.3 for the single-population professor model also are used in the two-population professor-student model. Additionally, we choose the numerical value of the overall student population of our university to be

$$S_T = 3000, \tag{8}$$

and we assume that we initially have

$$S(0) = 500 \tag{9}$$

successful students in that population.

The system of equations (5) and (7) is solved numerically through Matlab 5.3 using a variable-order stiff differential equations solver [80].

5.7 Stage 2: The Professor-Student Model - Results

In this section we present numerical solutions to the system of nonlinear equations describing the interaction between the professor and student populations, given by Equations (5) and (7). We again consider three scenarios: maintaining government funding, reducing government funding, and increasing government funding.

Case 1: Maintaining Government Funding. The impact of maintaining government funding on the professor and student populations is shown in Figure

5. Neither population exhibits much dramatic change for the first thirty to thirty-five years. In this time, the productive professor population is slowly but steadily climbing, while the the successful student population is actually decreasing very slowly over the first two decades. The student population then begins to increase steadily as well, slowly at first, and then more dramatically after year thirty-five. It is interesting to note that the presence of even low levels of good students has a sufficiently positive effect on the professor population so that by year thirty-five, the successful professors constitute about 20% of the total population, up about 17% from the first year. (Compare this with our professor-only model, in which an increase of only about 1% is seen over the entire fifty-year span.) The initial decline in the successful student population seems to indicate that a population of productive professors that constitute less than about 10% of the total population is not sufficient to attract successful students to the university. Once P becomes large enough, however, we see S begin to rise as well. Between years thirty-five and fifty we see a significant increase in both the levels of productive professors and the levels of successful students, with the student population growth lagging slightly behind that of the professor population.

[Fig. 5 about here.]

Case 2: Decreasing Government Funding. Figure 6 shows the effect of steadily decreasing government funding by 5% each year. It is interesting to note that the negative impact of decreased funding is somewhat offset by the presence of successful students. The model predicts an initial very slight increase in the productive professor population. This increase is sufficient to delay the eventual decline in the productive professor population by approximately five years, but after year five the population of productive professors decreases rapidly and is down to essentially zero after two decades. The student population sees only a monotonic decrease from year to year, since the professor population is never able to get over the critical threshold that would encourage an increase in the number of successful students.

[Fig. 6 about here.]

Case 3: Increasing Government Funding. In Figure 7, we see the positive effect of steadily increasing government funding by 5% per year. In this scenario, the growth in the productive professor and successful student populations is greatly accelerated compared with when government funding is simply maintained. The productive professors will constitute at least 90% of the total professor population in a little over fifteen years, while the student population will be 90% successful just a few years after that.

[Fig. 7 about here.]

5.8 Stage 3: The Professor-Student-Industry Model - Equations

We now add a population to our system of equations that will allow us to model the change over time in the number of industrial positions available in the university region. We let $H(t)$ represent the number of industrial positions in the region at time t. As indicated by the dependencies graph in Figure 1, the equations for P and S remain unchanged. This reflects the assumption that the presence of industry in a university town does not significantly affect whether a professor is productive or whether a successful student chooses to attend that university. On the other hand, based on evidence such as that discussed in section 2.3, we assume that the presence of both successful students in the area and the availability of productive professors to do consulting work, for example, will affect the growth in H. The implicit assumption here is that industry jobs are those requiring college degrees, directly fillable by university graduates. Additionally, we assume that H is positively affected by the number of other industrial positions currently in the region but that there is also a saturation point, H_T, beyond which the market can no longer grow. We link this saturation point H_T directly to the population in the region, in this case a multiple of the total of professors and students together, so that

$$H_T = m(P_T + S_T),$$

where m is some positive constant. The equation describing $H(t)$ is given by

$$\frac{dH}{dt} = e_0 H \left(1 - \frac{H}{H_T}\right)\left(e_1 \frac{\beta P - P_T}{P_T} + e_2 \frac{\gamma S - S_T}{S_T}\right), \tag{10}$$

where e_0, e_1, and e_2 are scaling parameters. The term $e_0 H$ says that H grows proportionally to itself (i.e., if there are already industrial jobs in the area, it will attract more industrial jobs). This term is multiplied by $(1 - H/H_T)$, which says that there can be saturation in the market. That is, once we start getting near to having H_T jobs in the region, the growth in the number of industrial positions will slow and will level off at H_T jobs. The last two terms, $(\beta P - P_T)/P_T$ and $(\gamma S - S_T)/S_T$ say that if the *productive* professor population drops below the fraction $1/\beta$ of the *total* professor population, and if the *successful* student population drops below the fraction $1/\gamma$ of the *total* student population, this will have a negative impact on the growth in the number of industrial positions in the region.

5.9 Stage 3: The Professor-Student-Industry Model - Numerics

As in preceding sections, all the numerical values already assigned to known parameters will remain the same for these experiments. Additionally, we assume that the initial number of industrial positions in the region is

$$H(0) = 1500. \tag{11}$$

Recall that we start with conservative initial conditions. If the region started with a critical mass of good professors and students, the economic development process could be jump-started by years.

We allow the job market to grow until the number of industrial positions is three times that of the total university population, so

$$H_T = 3(P_T + S_T). \tag{12}$$

We also choose

$$1/\beta = 1/5$$

and

$$1/\gamma = 1/3.$$

This says that if the productive professor population drops below 20% of the total professor population, and if the successful student population drops below 33% of the total student population, the number of industrial jobs in the region will be negatively affected. We note that our initial productive professor population is a little over 3% of the total, while the initial successful student population is a little over 16% of the total. This means that in all cases we expect to see an initial decline H, at least until the successful student and productive professor populations can achieve their critical thresholds.

As with the one-population and two-population models, the three-population system, Equations (5), (7), and (10), is solved numerically through Matlab 5.3 using a variable-order stiff differential equations solver [80].

5.10 Stage 3: The Professor-Student-Industry Model - Results

Numerical solutions to the three-population system of equations, Equations (5), (7), and (10), are given in this section.

Case 1: Maintaining Government Funding. In Figure 8 we see the evolution over time in the number of industrial jobs in the region when government funding to the university is maintained. As expected, because of the thresholds set, industry is reduced by about 85% by year fifteen, and reaches critically low levels by year twenty. However, as the student and professor populations begin to affect each other positively, and those populations begin to increase, industry follows. By year forty, both the productive professor and successful student populations are close to maximum levels, and at this point H begins to take a turn for the better. By year fifty, H has already enjoyed an increase of 80% relative to its all time low in year forty-one. However, levels are still at only 4% of their all time high, which took place in year one.

[Fig. 8 about here.]

Case 2: Decreasing Government Funding. The effects of decreasing government funding can be seen in Figure 9. The professor and student populations behave as before, and, unsurprisingly, industry dies out completely. This time, it takes only fifteen years to reduce H by over 85%, and by year thirty, H is essentially extinguished.

[Fig. 9 about here.]

Case 3: Increasing Government Funding. We see a more optimistic picture in Figure 10, which reflects the outcome when government funding is steadily increased by 5% each year. It is interesting to see how the development of industry lags behind the growth in the productive professor and successful student populations, but does follow them. The increase in government funding allows industry in the region to flourish, after an initial ten-year to fifteen-year decline in which the professor and student populations are developing. By year fifteen, industry is on the upswing, and by year twenty-two, H has over doubled in sized from year one. Five years after that, H has reached over 95% market saturation and is over six times as large as it was in year one.

[Fig. 10 about here.]

6 Discussion

While most university economic impact studies examine the regional impact of the presence versus the complete absence of the institution, this study incorporates deterministic mathematical modeling in order to contribute to the understanding of the effects of modifying funding levels on the inner workings of the organization, and the consequent economic influences on the region. We have developed a system of simultaneous differential equations, based on the theory of diffusion of innovation, to model the continuous time effects of interacting mutually dependent phenomena. We propose that the well-known beneficial effect of the university upon the regional economy can be severely compromised by ill-thought-out budget cuts and that continually diminishing financial resources to the university will result in reduced benefit to the community. On the other hand, our mathematical model shows how healthy government financial support of universities can create a resonating economic effect, causing state university towns to flourish.

While numerical simulation results do indicate that the effects of budget cuts can severely impact the university's functioning, the experiments also reveal that the full impact of these cuts may not be realized for decades. Similarly, steady budget increases can influence the university positively, but again, these influences are often only observed over longer time frames.

In our current culture of examining results every fiscal quarter, or at best at the end of a four-year administration, the careful consideration of the long-term impact of policy decisions is too often neglected.

6.1 Future Directions

The results that have come out of this investigation can be useful in directing future research endeavors. For example, the parameter sets chosen for use in this model have been determined from general assumptions, which in turn arose from evidence in the literature. Although the simulation results make sense from an intuitive standpoint, exact data and measurements for use in this model are unfortunately lacking. The numerical simulations are instructive in that they identify possible trends and outcomes, but these trends may vary depending on the parameter set reflective of a particular institution. In order to be able to apply this analysis framework to an actual university situation, it would be necessary to employ organization-specific numerical values. It would be of great use to conduct investigations to collect empirical data that could allow for the determination of more precise model parameters.

Any additions to the fundamental structure of the model are likely to make the model far more complex. Nonetheless, we present some possible model extensions for future research.

It was implicitly assumed in the mathematical model that money budgeted toward the encouragement of productive activity was well placed and effectively used by some measure. In future refinements of this model, we plan to examine this assumption more closely, focusing on how funding is apportioned within a university system and what the known outcomes of that apportionment are.

In the current model, the respective populations of professors and students are categorized as either productive or not, successful or not. We plan to explore the possibility of allowing for multiple levels of productivity and success, or even a continuum of such. Such a variation in levels of productivity and success is more reflective of a true university population.

The model presented here incorporated the assumption that total populations of students and professors were unchanging. However, significant growth in the number of students enrolled and the number of professors employed at a university could, in and of itself, be interpreted as a measure of the success of that university. A future extension of this model will allow for fluctuations in total population sizes.

In this model we did not consider the financial impact of the presence of students. In a future model refinement, we plan to include the effects of tuition income, of raising and lowering tuition levels, and of providing student financial aid as well as merit scholarships and analyze how these decisions in turn affect the student population and diversity. We would also like to examine the effects of activities not directly tied to the teaching and research missions of the university, such as athletics, community outreach projects, and continuing education.

The fundamental mathematical framework developed in this paper, while instructive in its own right, is intended to serve as a foundation from which to build models that are even richer in detail and that would allow for a greater degree of fine-tuning. Ultimately, the goal is to be able to employ this deterministic approach, in combination with collected data, to allow policymakers to develop well-informed budgeting level and apportionment plans tailored for long-term societal benefit.

6.2 *Challenges to Implementing These Findings*

Despite our optimistic hope that the mathematical framework we have developed and the simulated outcomes that are generated through the framework can eventually be of use to policymakers, and in turn of benefit to university regions, a number of cultural and societal roadblocks currently hinder the implementation of the findings of both this work and other related findings in the literature. We suggest that the following fundamental philosophical and societal shifts regarding the use of public funds must first take place before these results will be able to enjoy a degree of significant impact.

- In order for these results to be understood to the point of finding their way into policy-making, the public, which is responsible for electing decision makers and politicians, must be active and well informed. As Knack and Keefer state, "Knowledge of politics and public affairs by large numbers of citizens, and their participation, are important potential checks on the ability of politicians and bureaucrats to enrich themselves or narrow interests that they are allied with" [50, p. 1252].
- Both the ability to consider long-term effects and the ability to endure very delayed gratification are required by policymakers and public alike.
- Public funds must be channeled into an area (higher education) that is not necessarily popular or profitable for policymakers, and may even be viewed as elitist.
- Elected officials must acknowledge the importance of programs that will pay dividends only after their term in office ends.

Nonetheless, we believe that studies such as this one contribute to the body of knowledge that will encourage the cultural changes necessary to allow a society to understand the importance of a healthy higher education system and to "think long-term" toward supporting the development and nurture of such a system.

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List of Figures

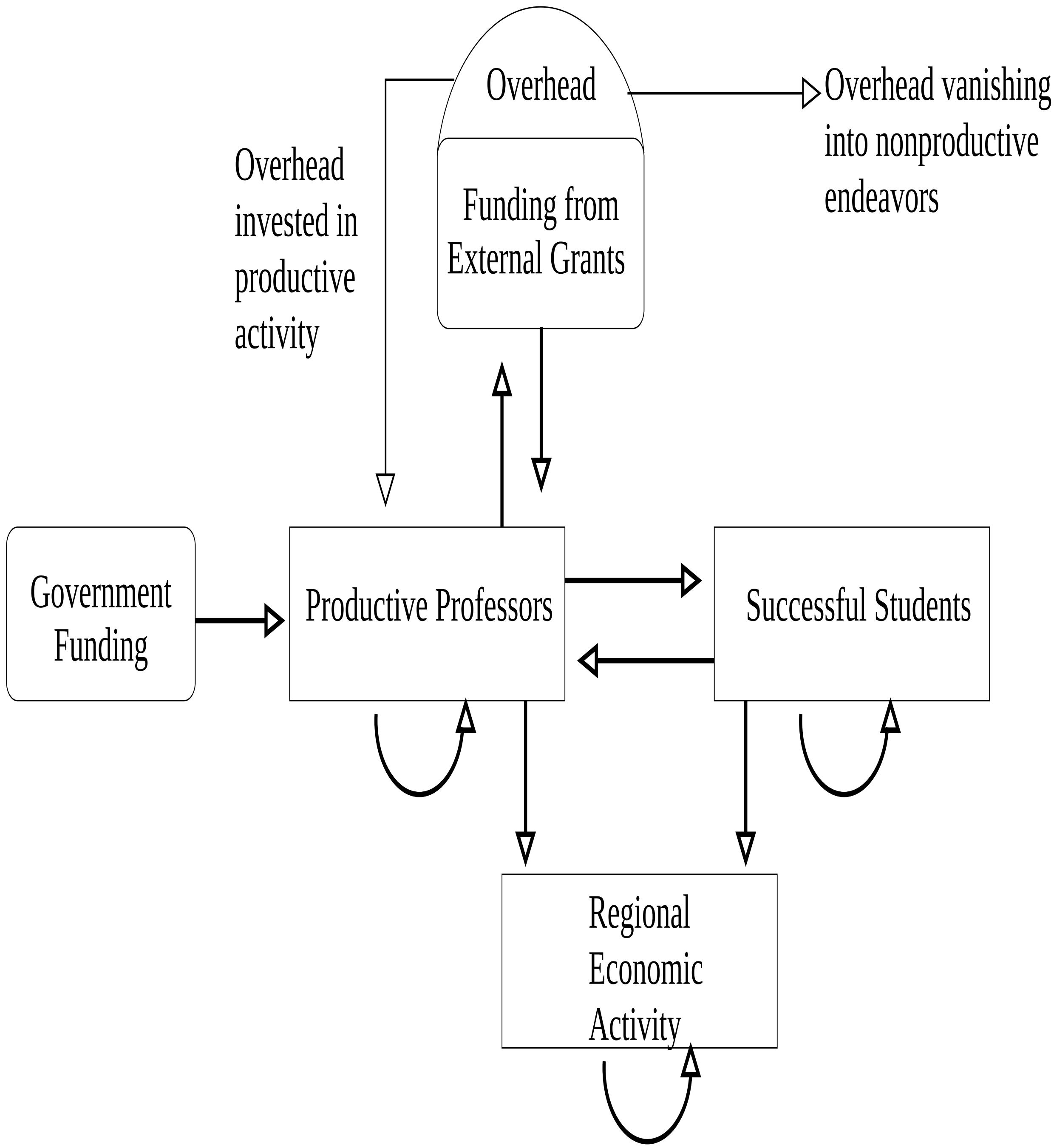


Fig. 1. Simultaneous dependency flow chart for mathematical model of a university dynamic.

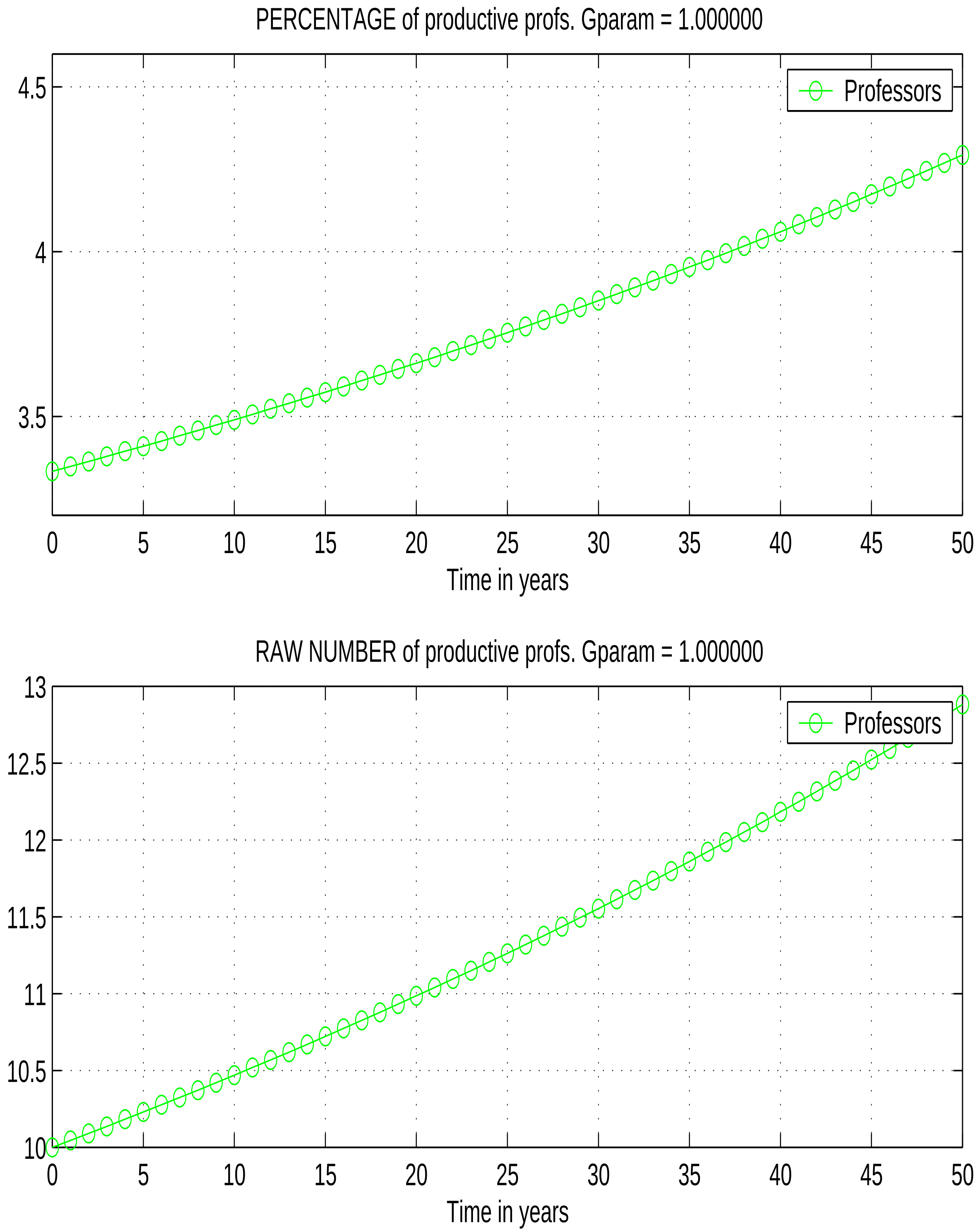


Fig. 2. Effect of maintaining levels of government funding from year to year.

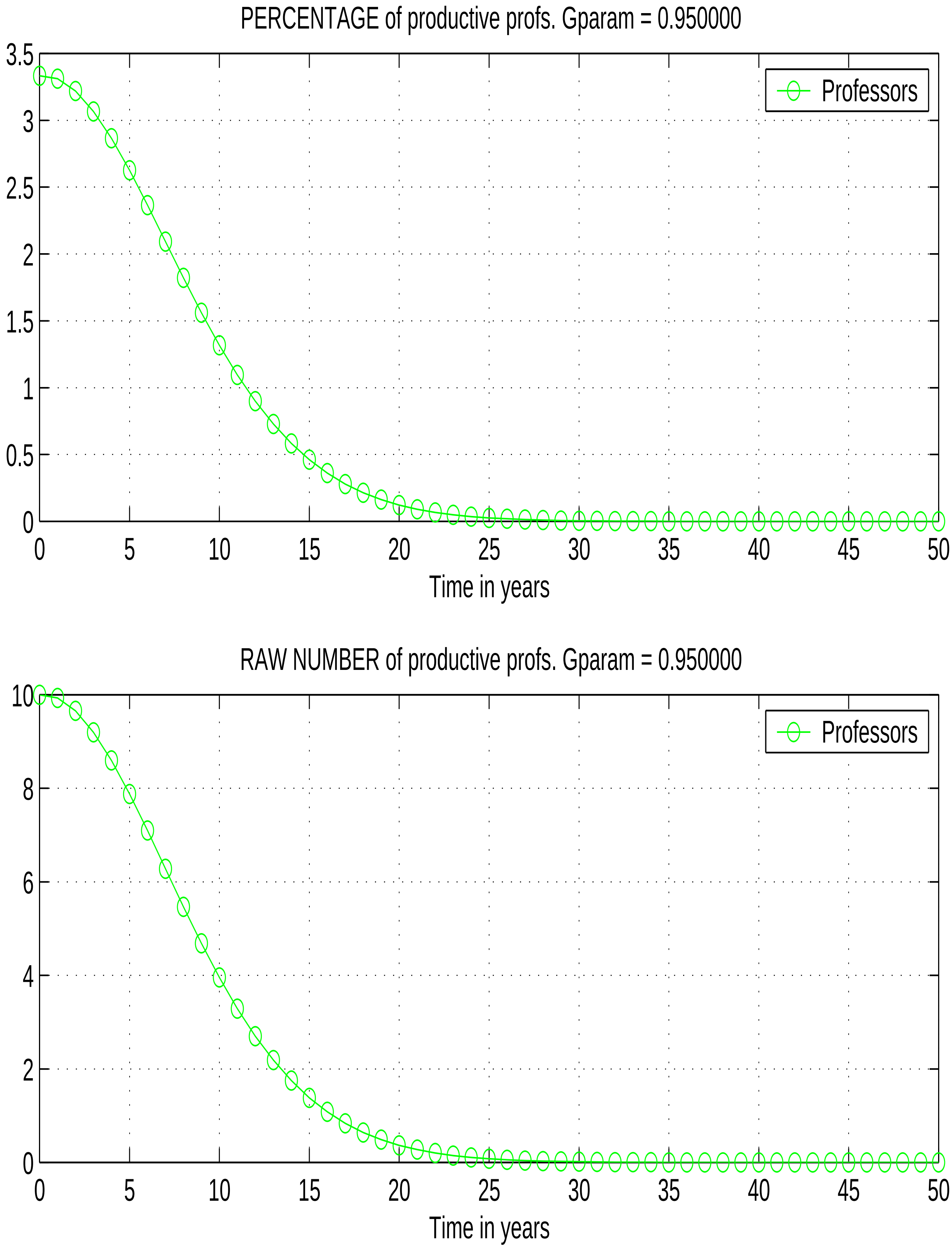


Fig. 3. Effect of decreasing government funding by 5% each year.

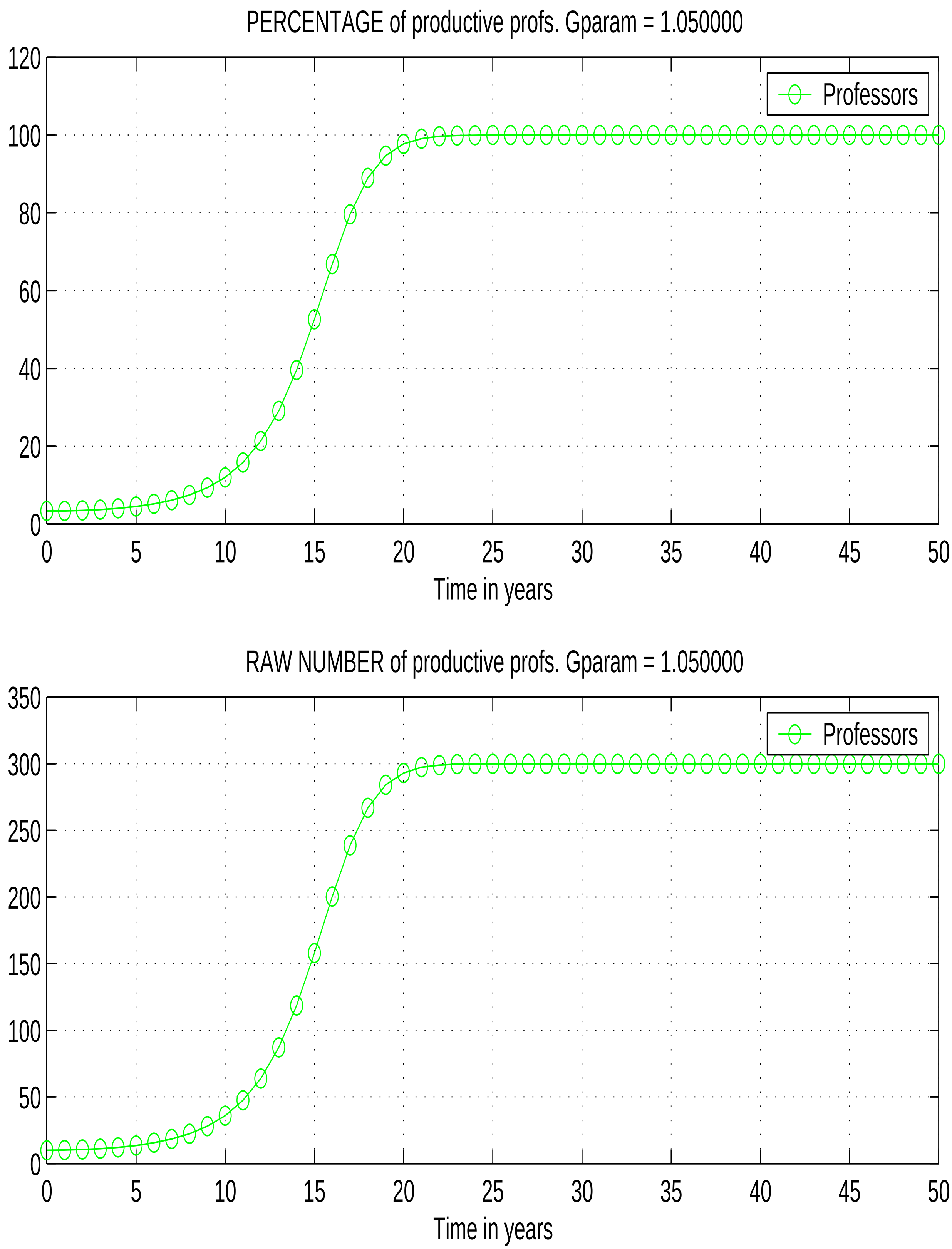


Fig. 4. Effect of increasing government funding by 5% each year.

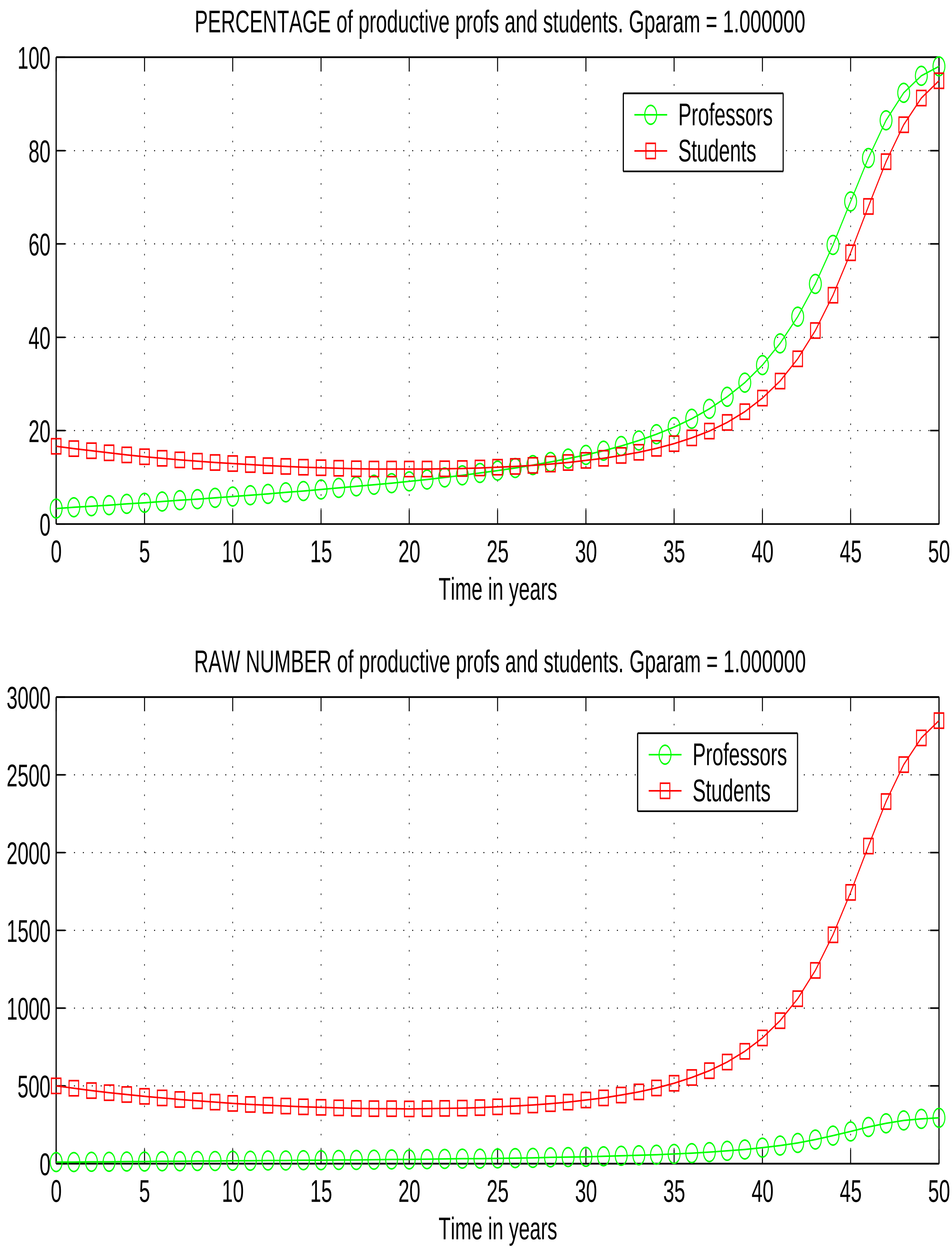
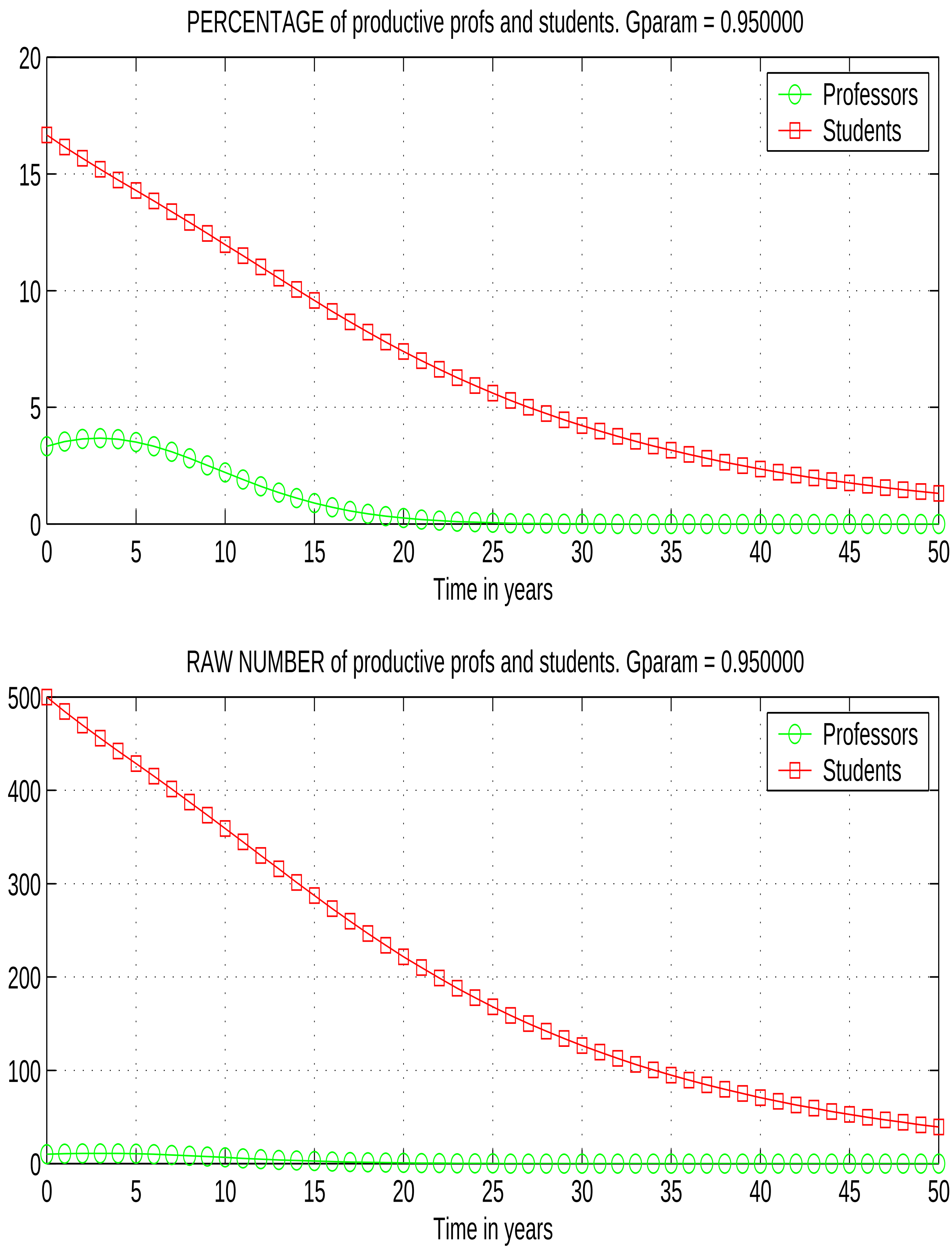


Fig. 5. Effect of maintaining levels of government funding from year to year.



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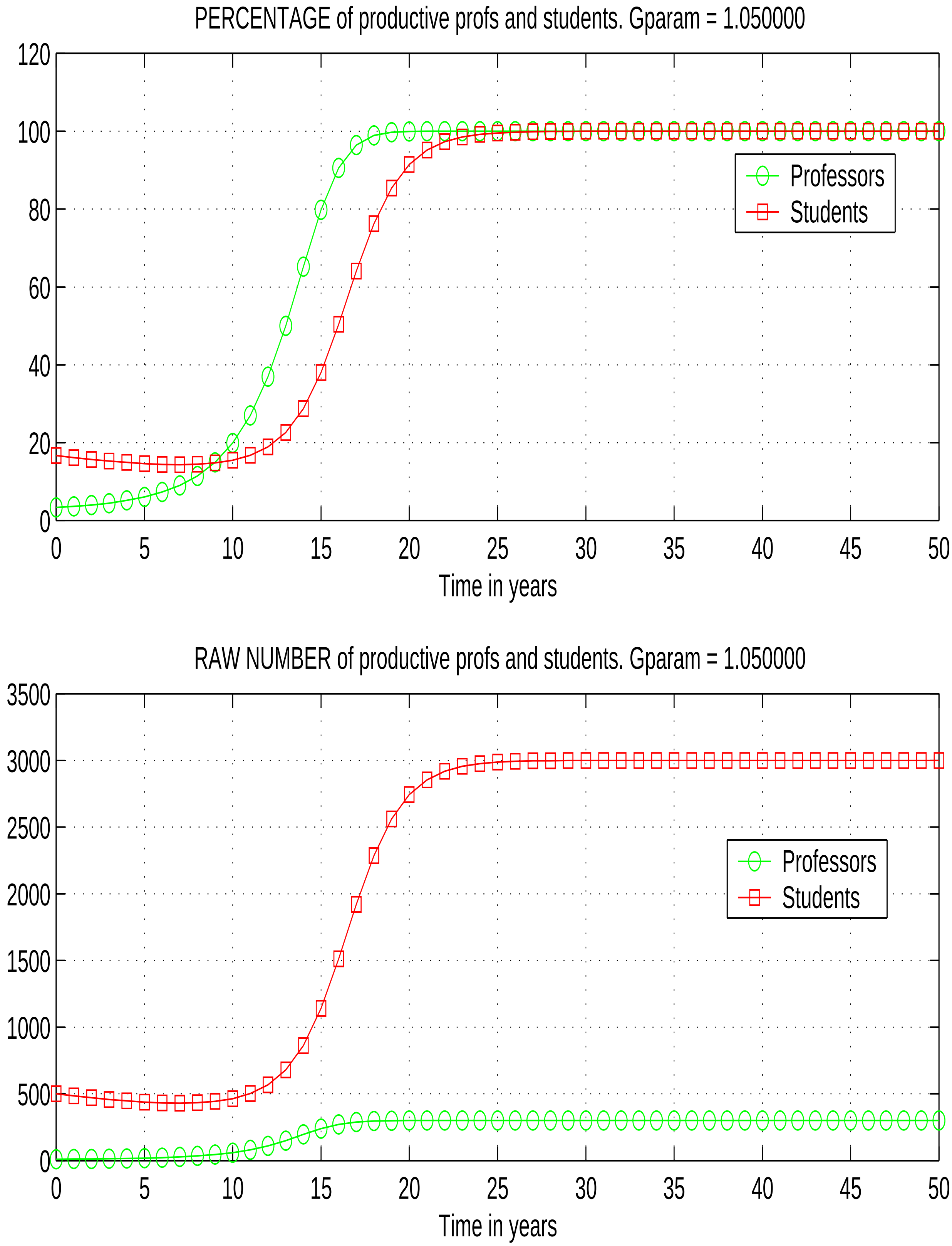

Fig. 7. Effect of increasing government funding by 5% each year.

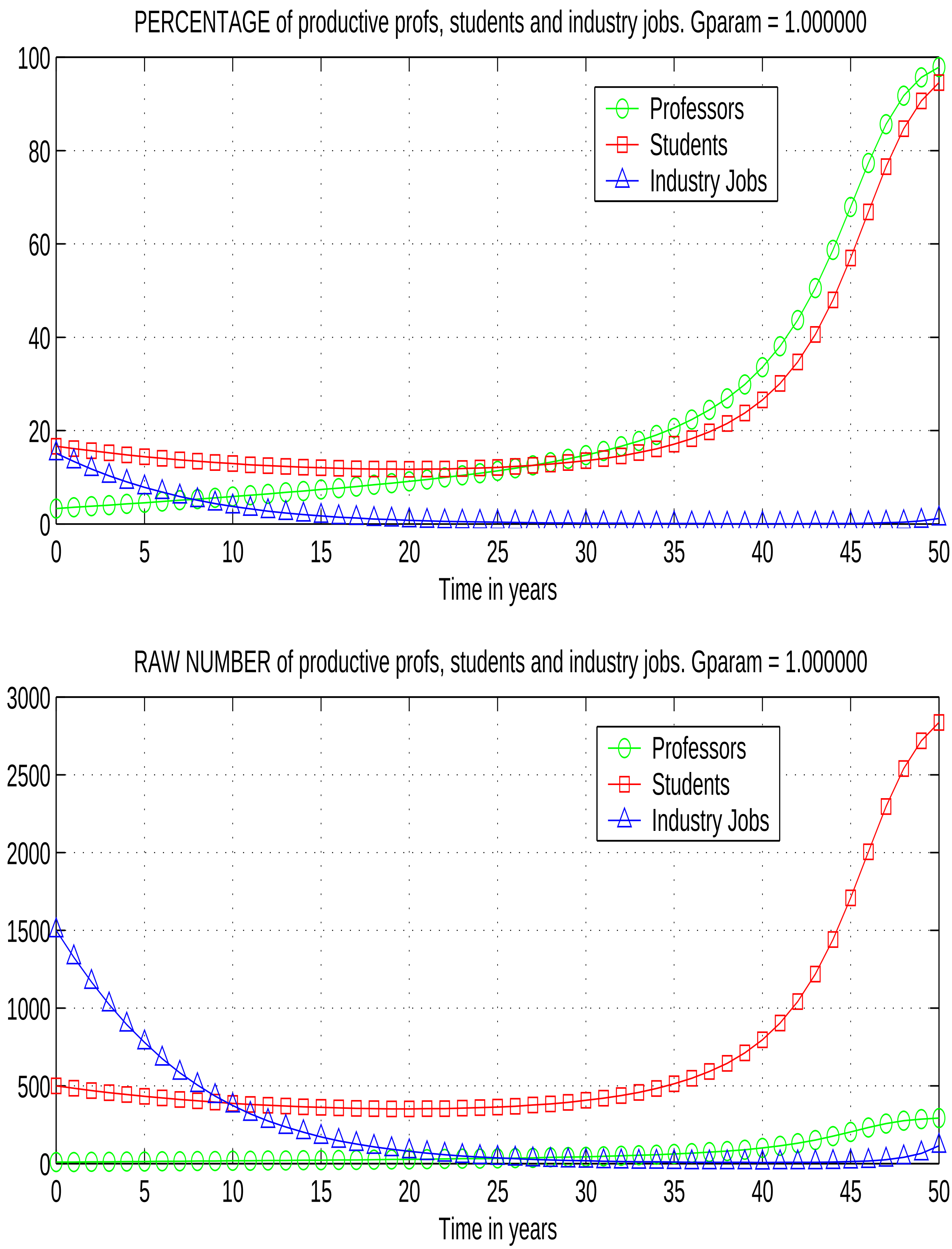

Fig. 8. Effect of maintaining levels of government funding from year to year.

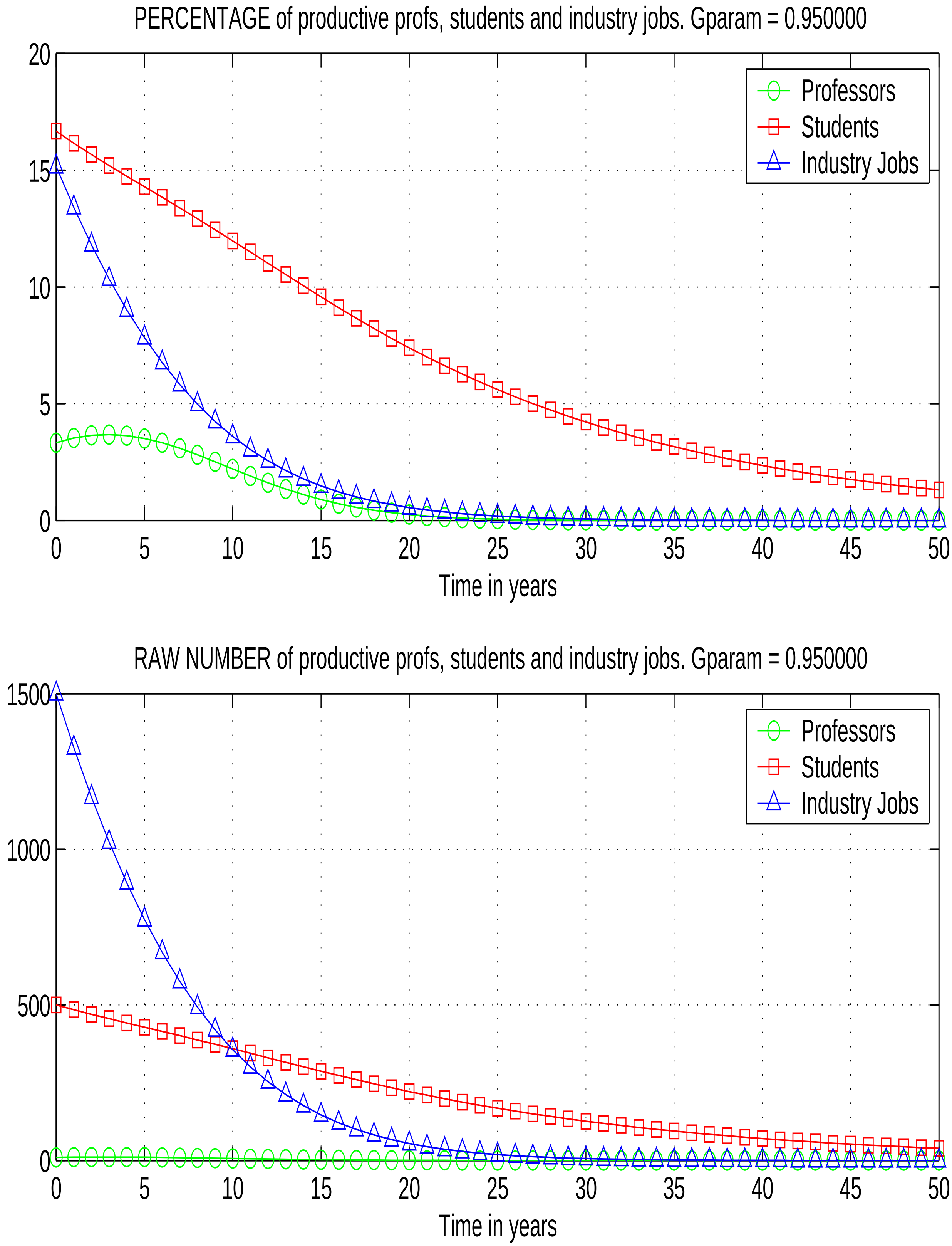

Fig. 9. Effect of decreasing government funding by 5% each year.

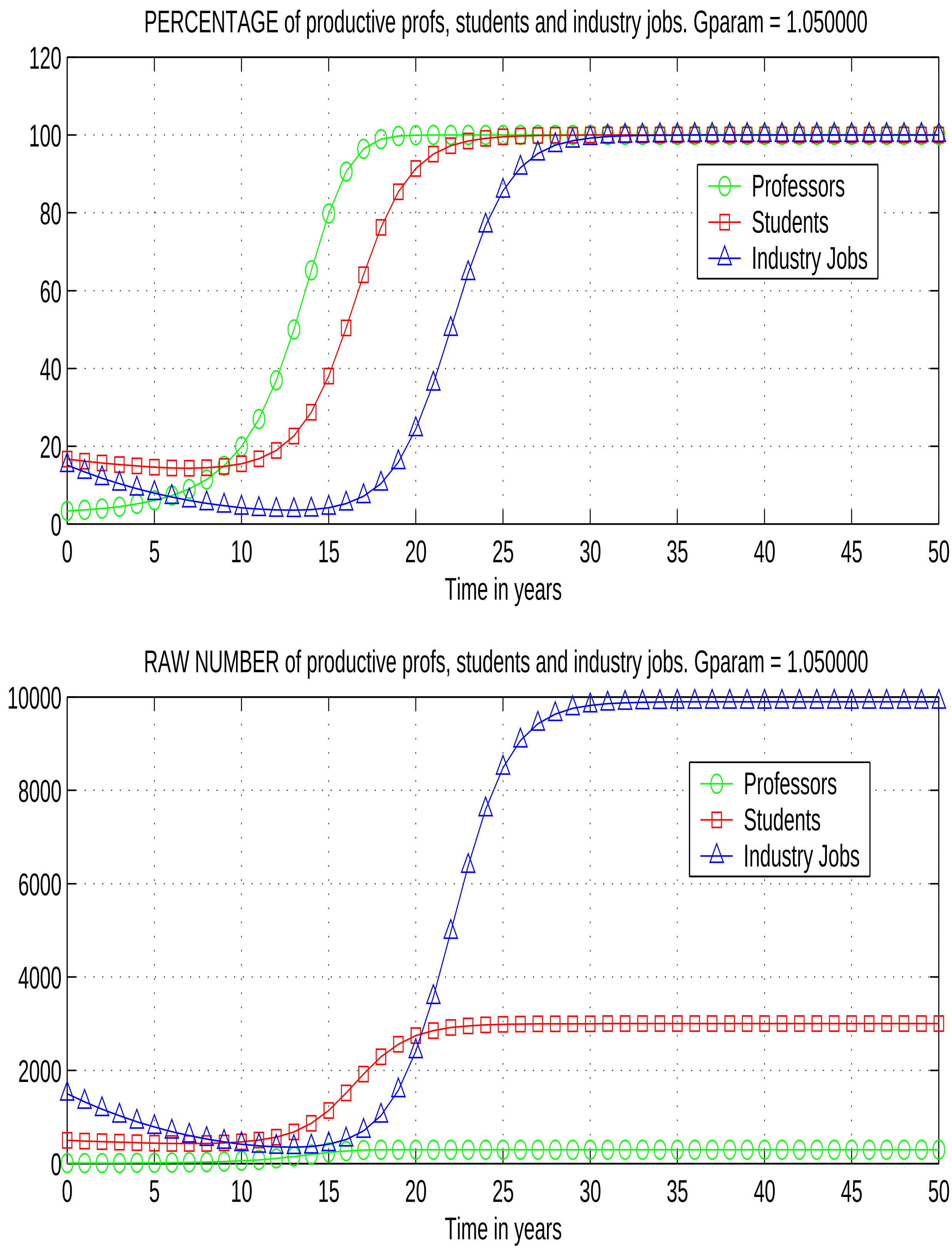

Fig. 10. Effect of increasing government funding by 5% each year.