Building an Integrated High School Curriculum Focused on the Biology and History of Smallpox

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Recently we were challenged to develop curricular materials to explore system dynamics as a foundation for engaging high school students in interdisciplinary studies. We needed to: engage student interest, be responsive to the schools' need to meet specific learning standards, foster an appreciation for crossing traditional disciplinary boundaries to address "real-world" issues, and provide students and teachers with opportunities to develop system dynamics mind-sets and tool-sets that could transfer to other scenarios.

We revised our collegiate course, "Plagues and People," that focused on the impact of epidemic disease on human history. Here we chose to focus consistently on a single disease, smallpox, that has, over millennia, killed more than 100 million individuals.

The package consists of 10 case studies; four of the cases have a primary biological focus, four focus on history, and two are interdisciplinary. Each is designed to be free-standing, but to also draw on the insights from other cases and to lead into yet others. Each utilizes a variety of system dynamics-based explorations and provides opportunities for students and teachers with widely differing system dynamics exposure and ability. Collectively, they provide a rich mosaic of intellectual explorations that bridge traditional but limiting barriers separating academic disciplines.

Introduction:

Over the last decade, educators have become increasingly explicit and forceful in articulating the need for middle- and high-school students to understand and deal effectively with the interrelationships of the myriad systems that surround them. All state Standards and Frameworks of Education that we have encountered speak, explicitly and implicitly, of the need to provide students with the mental frameworks to better understand “systems,” to make connections across traditional disciplinary boundaries, and to develop the means and inclination to critically evaluate how the “real world” works and how it affects individuals, their communities, and the globe.

This desire, however, often founders when challenged to operate within the limits of the current pedagogical paradigm. Much of current secondary and middle school education is focused on and organized by a set of disciplinary areas that date back decades to centuries. Math is taught by math teachers in the math classroom during the math period; history is taught by history teachers in the history classroom during the history period, and so on. There is a powerful inertia in the educational system that seems to seek to maintain a comfortable, if not terribly effective, *status quo*, even in the face of widespread appreciation that the issues and opportunities that will greet these students in the “real world” are not limited by or contained within such neat disciplinary walls.

Related to this disciplinary focus is a focus on a body of facts that the current system believes a properly educated individual needs to know. These facts were developed and organized in the disciplines and have resided in and been refined in those disciplines, often for long periods of time. The academic residents of these disciplines have an ownership interest in the integrity of these bodies of facts. In addition, these canons of knowledge are familiar and comfortable to the rest of us; it is easy for us, through our own educational experiences and memories to focus on them. Much more difficult is to focus on more recent aspirations of the educational system -- to aid students’ generic critical thinking and analytical skills that are valuable in diverse areas that cross these disciplinary boundaries, to encourage students to develop the means to construct their own knowledge and insight on their own and in teams, to help students see the functional similarities in systems from different areas of human endeavor, and to prepare students to explore and deal with issues and circumstances that have no established place within any disciplinary walls.

Recent efforts to develop system dynamics as a set of tools for K-12 education have been stimulated by the recognized need to move beyond this tight focus on facts and isolated, individual disciplines to more creative and transferable analytical skills that are broadly applicable to real world problem-solving. Progress has been slow but discernable, as more and more teachers and administrators are being trained in “systems thinking and dynamic modeling,” as the Creative Learning Exchange has recognized in a series of bi-annual meetings to highlight and share the advances being made. In addition more and more curricular material is becoming available for teachers to use and adapt without having to build each piece from scratch. Much of this new material, however, is episodic, in that it represents a one-time appearance of system dynamics in a particular course. In addition, much of this work is still rooted in specific disciplines and makes little effort to translate itself beyond those initial foci.

We at the Waters Center for System Dynamics have, for a long time, been struck by similar arguments that could be made about college/university education, the domain in which we have principally lived. Development of interdisciplinary college courses has been one of our primary efforts over the years; we have reported on several of those experiments at these meetings (Heinbokel and Potash, 2000; Potash et al., 1998). We have also had the luxury of advocating similar curricular development at pre-college levels, but without accepting any real obligation to help make it happen.

In discussions with K-12 colleagues at the Bergen ISDC and other gatherings last year, we apparently advocated for such pre-college curricular development once too often. We were challenged, and offered support (a powerful combination), to devise or adapt material to create a integrated, interdisciplinary, system dynamics-based curricular unit that would benefit secondary and, perhaps, middle grades students. The material (10 interconnected "case studies"on the history and biology of smallpox) that we describe in the following text is our response to that challenge.

<u>**Smallpox as a Theme for Joining History and Biology**</u>:

The outbreak of epidemics has had a tremendous impact in shaping the human experience, in the context of the past, the present, and the possibility for future epidemics. We developed this theme, focusing on the impact of disease on the course of human history, several years ago through a course, "Plagues and People," developed for students at Trinity College and then adapted three years later for a mixed audience of educators and honors-level high school students. This course developed a fundamental, systems-based appreciation for the dynamics of infection and then applied that core structure/behavior to a number of episodes that focused on disparate diseases and historical epochs, terminating with an examination of the current HIV/AIDS epidemic. This was a satisfying experience for us as collegiate instructors, but we realized that few high schools could or would choose to devote an entire semester to an integrated theme such as this. We needed to adapt this topic into a series of case studies with a unifying theme so that teachers could pick and choose from an abundant and interrelated and mutually supporting set of materials to support their individual classroom needs. The original "Plagues and People" materials were simply too wideranging and idiosyncratic for that sort of development. We chose instead to focus on smallpox as a single disease with which to explore a variety of related biological and historical dynamics.

Smallpox, as an integrating framework, allowed us to combine disciplinary material that is, or can be, part of the health, social studies/history, and biology curricula while, at the same time, providing a vehicle for pulling together these often isolated subjects and for building a more generic appreciation for and skill-set in system dynamics. Smallpox has a number of specific "virtues" for such a curricular task.

- It is a relatively simple disease to model, without the non-human vectors of bubonic plague or malaria or the long-standing environmental presence of typhoid or other sewage-born diseases; it also has a reasonably well-defined time-course of infection and resolution.

- It has a long pedigree, being recognizable in the historical context for over two millennia; it is rich in illustrations.

- It has been significant in a wide variety of settings and has been, in total, responsible for a huge number of deaths; it is rich in impact.

- Its role in the development of vaccination as a public health tool and its ultimate eradication from the "wild" give it an historical place of priority.

- Even after eradication, it has maintained itself in the public eye, as the debate over destruction of remaining research stocks of the virus and its potential as a weapon of mass destruction make it a valid subject of ongoing concern.

General Organization of the Curricular Package:

We entered this curricular design exercise with several explicit goals in mind. Although each case study presents its own unique set of opportunities and limitations, we wanted the package as a whole to reflect a number of traits:

- It would be interdisciplinary, supporting teachers and students in linking biology and history especially, but also delving into economics, health sciences, and other disciplines.

- It would be based on a set of case studies by which to build those interdisciplinary lessons. While these individual case studies would often be grounded in a specific discipline, each would provide opportunities or obligations for connecting to concerns beyond the traditional boundaries of that foundation discipline.

- It would provide frequent opportunities for students to guide and control their pathways of learning; it would have "learner-directed" opportunities.

- It would be based on national or common state standards of learning that are being applied to science and social studies curricula across the United States.

- It would provide abundant problem solving opportunities and opportunities for students, having answered one set of questions, to devise and pursue a subsequent, better set of questions.

- Finally, it would be based on a foundation of systems thinking and dynamic modeling, providing students with an intellectual approach to problem solving and a set of modeling skills that would be transferable to diverse systems beyond the domain of this package.

Several additional realities helped to define the general organization of this set of smallpox-related case studies. First, and perhaps most fundamental, was our appreciation that teachers and students operate within today's educational system. However much we might be concerned about an over-dependence on an overly rigid disciplinary structure and on cataloging discipline-specific facts, that is, in most places, the reality within which the students and staff must operate. The individual case studies, therefore, had to appeal to the needs of teachers and students working within that system and to contribute meaningful and identifiable learning outcomes in that context for the students. The basic structure of each case study, therefore, has validity within one or more of the high school disciplines (e.g. health sciences, biology, history, and current affairs including economics).

An element of this challenge is that each case study needs to be capable of standing alone. Teachers of American History cannot be expected to wade through (or have their students wade through) a full account of smallpox in the Roman Empire of Marcus Aurelius in order to have the tools with which develop a fundamental understanding of the role of smallpox in clearing the native inhabitants from the Northeast United States. Biology teachers cannot be blocked from helping their students to develop an understanding of the human immune system because the previous year's health curriculum did not build a systemic appreciation for contagion.

In addition, each case study needs to be clearly built upon fundamentally important foundations in other disciplines and/or to support further elaboration of those other disciplines. While the units need to be capable of free-standing application, they also need to powerfully invite faculty and students to reach beyond the specific discipline in which the material is introduced. We need to demonstrate that a knowledge of biological dynamics enriches and enhances the historical insights that could be gained and that an appreciation of the historical dynamics provides a context and rationale for an incredible array of biological advances. In short the case studies need to fit comfortably within one or more disciplines but be simultaneously seductive in drawing both the teacher and the student into explorations that transcend the specific original discipline.

Another complexity in the design of these units is the variety of background in systems thinking and technical computer modeling skills that individual teachers and students will bring to these exercises. Some teachers are relatively skilled modelers and have developed the ability and a desire to support students in model building. Similarly students in a few, but growing number of, schools have had specific courses in, or other substantive introductions to, modeling. Where both faculty and students are prepared for such rigor, the challenge of building a number of these models pays powerful intellectual dividends. On the other hand some teachers and students may have a comfort with the systems thinking that underlies these exercises but be relative novices with the technical computer modeling. Here carefully guided model building challenges them to critically work with the structure and resulting behavior of these systems while providing practice in both the logic and mechanical skills of modeling. Finally, some teachers and students may profit from exploring a carefully crafted model of a particular system, but not have the time or the software resources to spend on constructing the model, even with extensive guidance. Accordingly, the smallpox case studies contain a mix of challenges for experienced modelers, supported practice for novices, and completed models with which beginners can explore the implications of various “policies.”

<u>Organization of the Specific Case Studies</u>:

To fully understand and appreciate the dynamics of smallpox, we chose to focus on two different sets of perspectives. One is the “scientific” by which to explore the biological dimensions of smallpox, and disease in general, including genetic resistance and acquired immunity as well as treatment and prevention. The second is the “humanistic” perspective with which to examine the social factors influencing the nature and rate of disease spread as well as its implications.

Over the past two millennia, smallpox has been the world’s most deadly disease, accounting for over 100 million deaths. The dynamics of epidemic outbreaks at intervals in world history, coupled with the introduction of immunization and eventual eradication of the disease, yields some powerful case studies. Within each case-study we seek to provide the necessary background material, to pose a series of progressively “better” questions, and to use the appropriate tools of system dynamics to guide the students sequentially to formulating an answer to the immediate question and to devising the next better question. Throughout each case study we seek to define how the system in question is behaving over time, what factors and feedbacks are controlling that behavior, and how that system could be (or could have been) affected by different policies or actions.

We follow our usual approach to case studies in this project. As we move through a series of related cases, we begin with one that illustrates and allows the students to develop the simplest and most fundamental understanding of the process or system in question. With that foundation they can then move to more complex or realistic scenarios and to connect the initial insights to additional social, historical, or scientific facets of the original issue or of related ones.

We have two possible frameworks on which to build a description of these case studies: a biological progression or an historical timeline. In fact we developed these materials so that either sequence can be used within the school setting. For the sake of a coherent presentation here, however, we present the biological sequence as the primary organizer and then relate the historical and social elements to that sequence. We chose this particular approach, not because it depicts a truly interdisciplinary approach (which we favor), but because it shows the clearest connections between the traditional disciplines that still form the core of most high school curricula, school district educational plans, and organization of statewide standards, within which most teachers must operate.

Table 1: Organization and Relationships of the 10 Case Studies that Comprise the "History and Biology of Smallpox" Curricular Package

Biology Case Study 1:
Fundamental nature and dynamics of the spread of contagious disease

Biology Case Study 2:
Customizing the basic infection model to smallpox.

> **History Case Study 1**:
> Smallpox in the time of Marcus Aurelius; beginning the demise of the Roman empire

Biology Case Study 3:
Exploring the natural selection of both the disease and its host's population.

> **History Case Study 2**:
> Cortez and the conquest of Mexico
>
> **History Case Study 3**:
> Impact of smallpox on native populations of North America

Biology Case Study 4:
The dynamics of immunity and of medical vaccination

> **History Case Study 4**:
> Repeated outbreaks in an urbanized society lead to variolation and vaccination
>
> **Combined Case Study 1**:
> Eradicating the disease.

Combined Case Study 2:
Bioterrorism

Biology Case Study 1 (Basic Dynamics of Disease Transmission):

This case study is designed to provide an entry-level appreciation for the dynamics with which a disease (not just, or specifically, smallpox) can spread through a population. It is based fundamentally on the work of Glass (1991), although one significant modification/correction to his epidemic structure needed to be made to account for the probability that any given contact would be able to transmit the disease.

Students and teachers are introduced to, reminded of, or given a chance to review a number of the basic tools and thought processes that are the foundation of system dynamics and that will similarly underpin the following cases. Based on the concrete experience of the role-playing game described by Glass (1991), students and teachers have the opportunity to experience the progression of a typical system dynamics exercise, exploring in turn:

- The behavior that is characteristic of a simplified disease transmission system (developing the use of “Behavior Over Time Graphs”),

- The role of reinforcing and stabilizing feedback loops in controlling and defining that observed behavior (developing the use of “Causal Loop Diagrams” and “Stock and Flow Diagrams” as summarizing and communicative tools), and finally

- The impact of initial intensity of infection, number of contacts per unit of time, and probability of infection from any one contact, on the anticipated dynamics (using computer simulations to explore these facets that will, eventually, provide many of the “policy levers” with which we will explore the ways and means to affect the dynamics of disease systems.

Figure 1 illustrates the basic behavior of this simplified system and the Stock/Flow and causal-loop structures that produce that behavior.

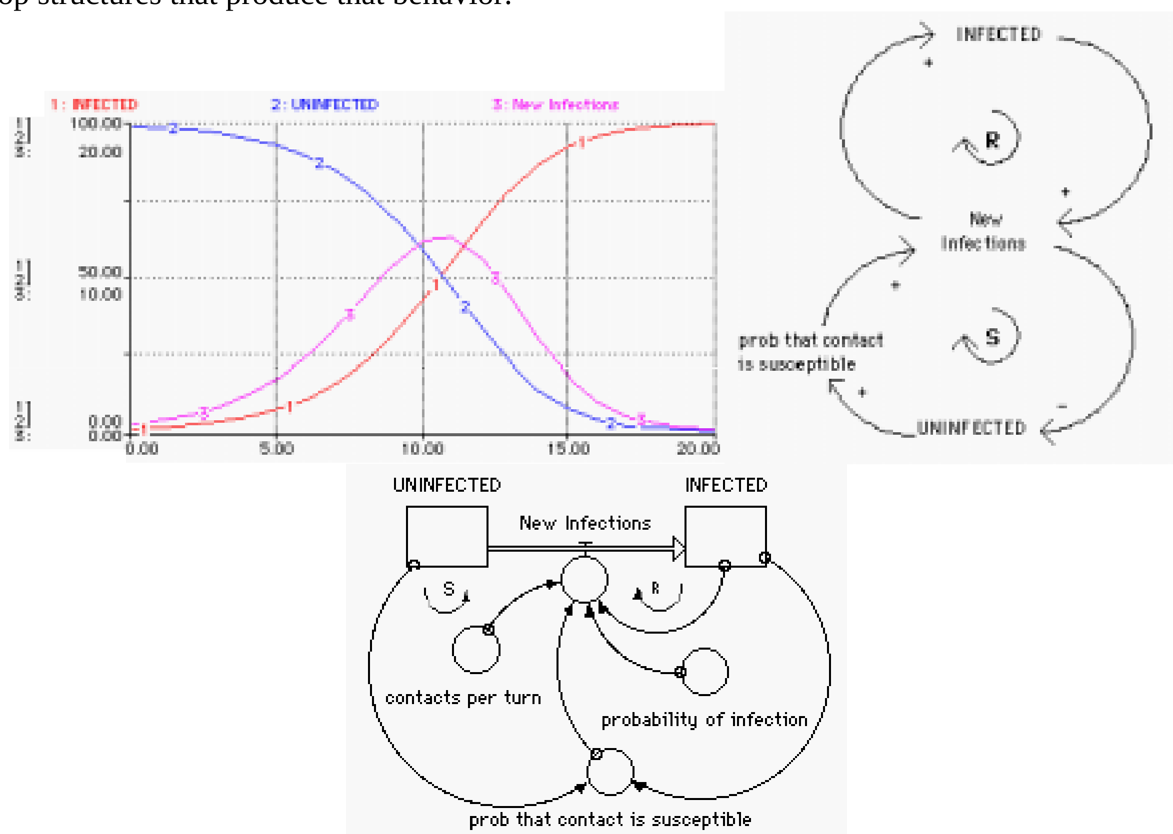


Figure 1: The basic disease transmission system developed in Biology Case Study 1 of the History and Biology of Smallpox curricular package.

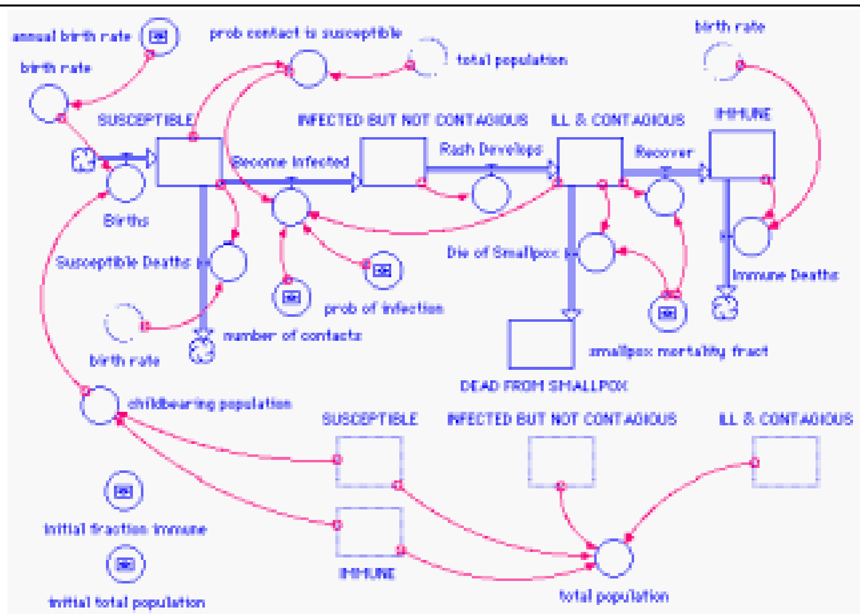
Biology Case Study 2 (Building a Customized “Smallpox” Model):

This case study builds on the basic dynamics of contagion developed in case study 1 (an abbreviated introduction to that dynamic is provided for those situations for which it is not convenient to go through the entire development of Biology Case Study 1) to build the core model of smallpox that will be used, or adapted, in many of the following units. The extension from the earlier model requires:

- The identification of a more complete and realistic set of stocks and flows to describe this specific disease. In particular we need the new model to reflect that there are two stages of the disease, an non-symptomatic and non-infectious incubation phase, and a symptomatic and contagious phase; that ill individuals will either die or recover; and that recovered individuals will be immune to smallpox in the future and be unavailable to catch the disease again.

- The recognition that real populations have open-ended (non-conserved) flows of births and non-disease deaths that must be considered.
- The inclusion of medically realistic rates of contagion, durations of stages, and mortality rates.

That model (Figure 2) is used to explore the impact of six specific factors that work together to control the dynamics of smallpox in a given population: “initial total population,” “initial fraction immune,” “annual birth rate,” “number of contacts,” “probability of infection,” and “mortality rate.” The graphs that accompany the model’s structure in Figure 2 are perhaps the least intuitive output from that sensitivity analysis, where we altered the “annual birth rate” over a factor of three.



Run #	annual birth rate
1	0.015
2	0.03
3	0.045

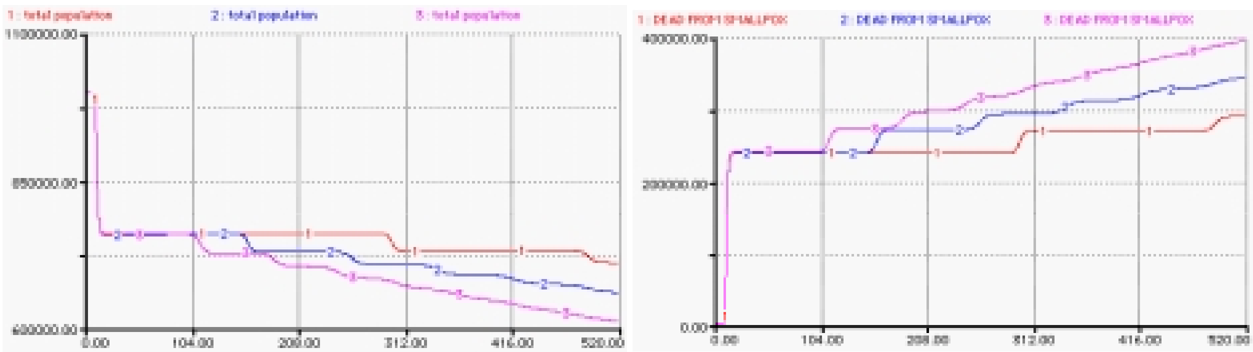


Figure 2: The basic smallpox model developed in Biology Case Study 2 of the History and Biology of Smallpox curricular package and the output derived from varying the "annual birth rate" factor. Note that distinct smallpox outbreaks occur repeatedly in this model. The amplitude and period of those outbreaks vary considerably depending on the characteristics of the population in question.

History Case Study 1 (The Antonine Plague of 165 - 180 A.D.):

The first major smallpox epidemic actually documented in western history struck the Roman army as it was returning from a successful Egyptian campaign. The impact of the disease was particularly pronounced over the next decade upon the Roman army as it struggled to quash an insurrection by Germanic tribes in the Danube region.

This event raises two major historical questions:

- How might the plague have affected the war effort? and
- How might the plague and war together have affected Rome in the longer term?

The absence of reliable historical documentation for the first question provides an excellent opportunity for modifying the generic smallpox model developed in Biology Case Study 2 by

- Replacing natural deaths and births with war deaths and new recruits
- Defining the army initially as 100,000 strong growing to 250,000 by 170 A.D.
- Incorporating war fatalities of 5% per year.

The results from this model illuminate a often-repeated historical pattern: while war deaths were anticipated, disease deaths--which exceeded war casualties here--were not.

To examine the ramifications of these unexpected war deaths, a second model was constructed, linking the Roman army with taxpayers and the imperial treasury (Fig. 3). Growing war expenses associated with unexpectedly large recruitment needs for an unpopular war combined with diminishing revenues to drain the treasury's reserves. The Stoic Emperor Marcus Aurelius, unable to sustain the war effort by disposing of his own personal wealth, was forced to consider two unattractive options, either acknowledge defeat at the hands of the Germans (which was impossible) or raise taxes (which, as Figure 4 shows, required a doubling of rates) for the unpopular war. In the end, he created a third option, reminting Rome's money. The long-term ramifications of this short-term "quick fix," form a excellent basis for a major discussion regarding the later fall of the empire.

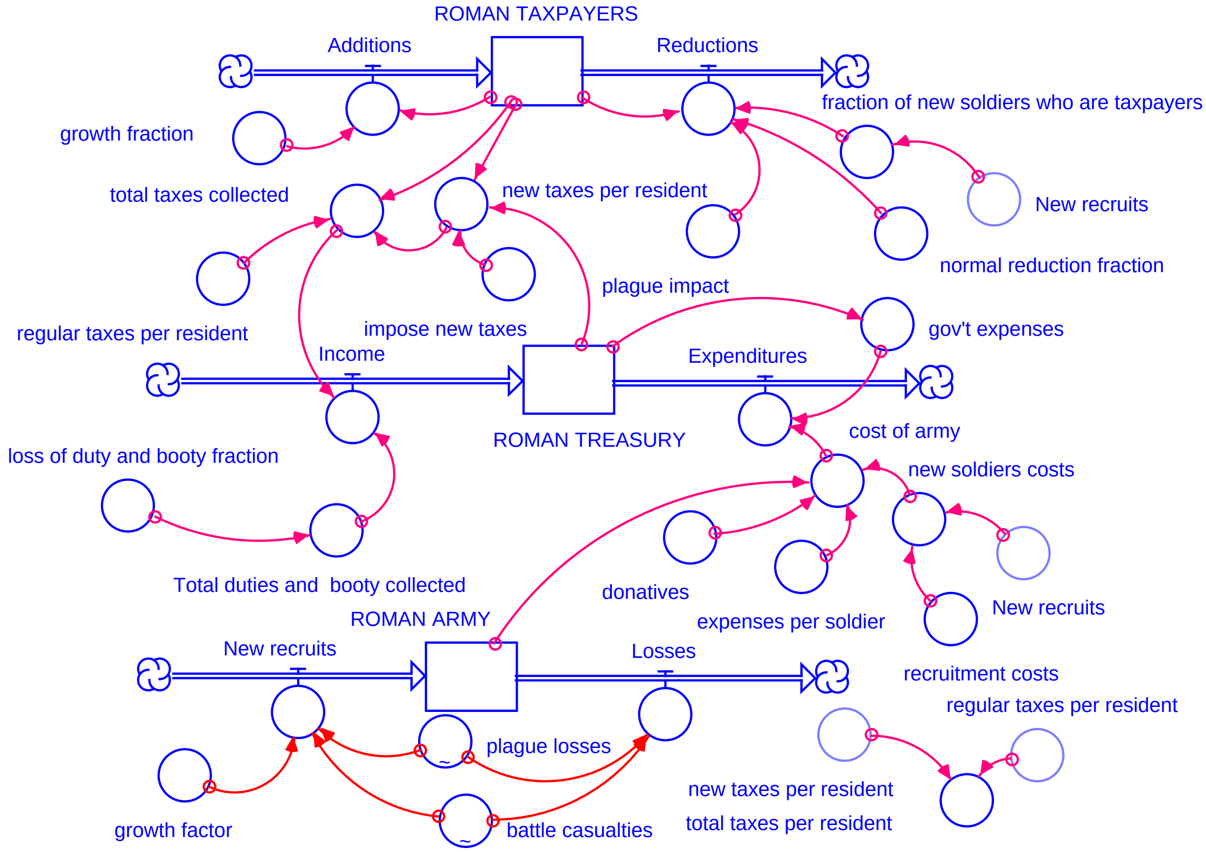


Figure 3: The Roman Treasury Model

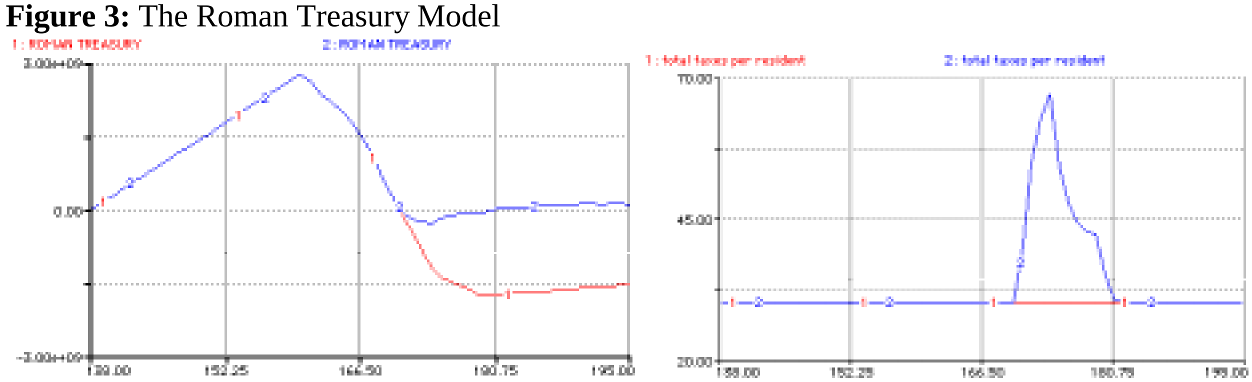


Figure 4: The Roman Treasury, with (#2) and without (#1) new taxes (see graph on right side for the taxes that would have been required to prevent bankruptcy of the Roman Treasury).

Biology Case Study 3 (Population Genetics):

This case study does not maintain a strict focus on smallpox but on the population genetics that characterize the relationships of many disease-host or parasite-host relationships, as well as many predator-prey dynamics. Natural selection acts on both the characteristics of the host as well as on the disease. McNeill (1976) presents historical illustrations of human populations becoming progressively less susceptible to the effects of particular diseases and of the disease itself apparently losing its virulence through repeated interactions. Population genetics, tracking and understanding the dynamic changes in the relative frequencies of specific genes and genetic traits, is a fundamental aspect of all biology curricula, profoundly influences the historical evolution of disease impact in human societies, and is wonderfully amenable to system dynamics exploration. After providing a quick review of the dynamics of smallpox from Biology Case Study 2, this unit:

- Adapts that basic smallpox model to track, over a 500 year period, the frequencies of two hypothetical human genes, one providing resistance to smallpox mortality, the other conferring susceptibility, and the three resultant human genotypes, homozygous resistant, homozygous susceptible, and heterozygous, as the model user adjusts the mortality rate of each of those three genotypes. Students have the opportunity then to build for themselves a somewhat simpler and more generic model of population genetics, one that serves equally well to describe these disease dynamics and other genetic dynamics such as sickle cell anemia. This generic model is illustrated in Figure 5.

- A similar exercise focused on the natural selection of virulence in the infecting organism.

- The final piece of this case study is a set of modeling exercises looking at the population genetics that underpin the development of antibiotic resistance in bacterial infections. This is not specifically germane to smallpox, a viral disease against which antibiotics are not useful, but it is a natural and useful extension from the generic population genetics models developed in this case.

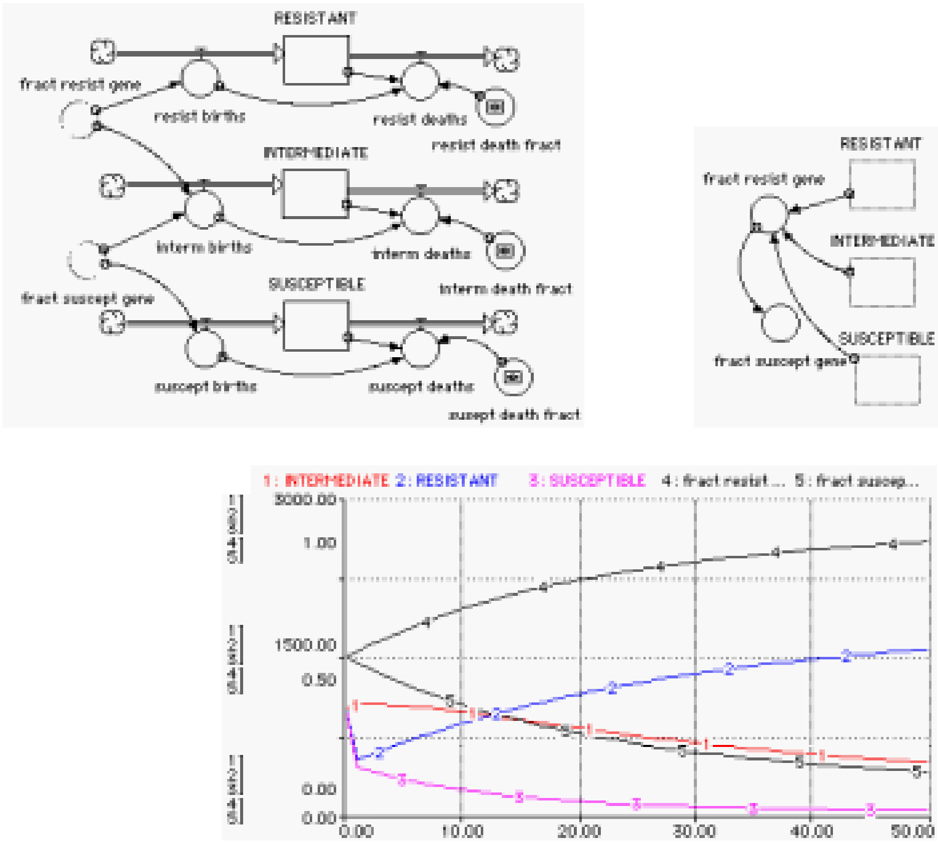


Figure 5: The generic population genetics model developed in Biology Case Study 3 of the History and Biology of Smallpox curricular materials. The illustration graphed here is for a model run that begins with the frequencies of the "resistant" and "susceptible" genes equal at 0.50 in the population; all three genotypes (the stocks) equal at 1000; the resistant and intermediate death fractions set at 0.30; and the susceptible death fraction set at 0.40. The susceptible gene is fully recessive in this illustration.

History Case Study 2 (Cortez and the Conquest of Mexico):

Historians disagree on the magnitude of the single smallpox epidemic which struck the Aztec capital of Tenochtitlan in 1521 during Cortez' incursion into the Aztec empire. Until recently, most historians discounted the impact of the epidemic, citing contemporary Spanish military accounts which make little or no mention of the event. Largely overlooked Aztec sources, however, describe an epidemic of 70 days duration with a significant number of deaths resulting. That raises a major historical question: "Was it guns or germs which defeated the Aztec in 1521?"

Biology Case Studies 2 and 3 develop the themes of acquired immunity and resistance which had enveloped much of Europe by this time. The Aztecs, subject to this "virgin soil" epidemic, however, had no such immunities. To reconstruct the likely impact of a smallpox outbreak, the generic smallpox model developed in Biology Case Study 2 was adapted as follows (Fig. 6):

- The outbreak is redefined to run on a daily basis

- In deference to the Aztec description of a period of time when the numbers of ill were so great that Aztec chroniclers reported a shortage of healthy caretakers to provide food or care, an "added mortality" factor was incorporated into the model.

Could the Aztec account be verified? Using a 30% mortality rate as the baseline, and incorporating the "added mortality from inadequate care" such that those in the final throes of smallpox who lacked a caregiver were likely to have died, the model generates output which "fits" the Aztec description. This output suggests the Aztec would have identified the epidemic's "start" some 50 days after the first infected individual entered the city. By this time, 100 individuals would be visibly sick, and 4 had died; the epidemic came to an "end" some 70 days later. If the epidemic "started" around October 1st, 1521, the individual who carried the disease into the city probably did so in early or mid-August. The epidemic then continued for 70 days or until mid-December. It is noteworthy, beginning on day 99 and continuing until day 112, the number of ill EXCEEDED the healthy population, thus triggering significant numbers of deaths among those described by Aztec sources as "abandoned" individuals (Fig. 7).

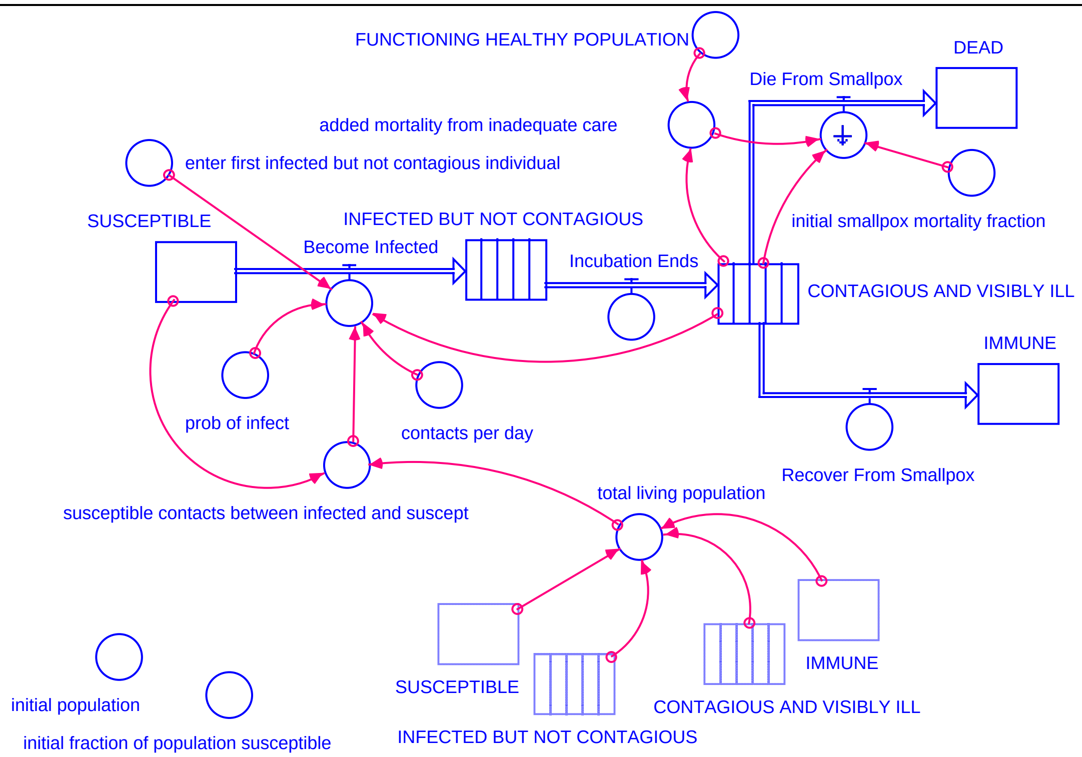


Figure 6: The Aztec Epidemic of 1521

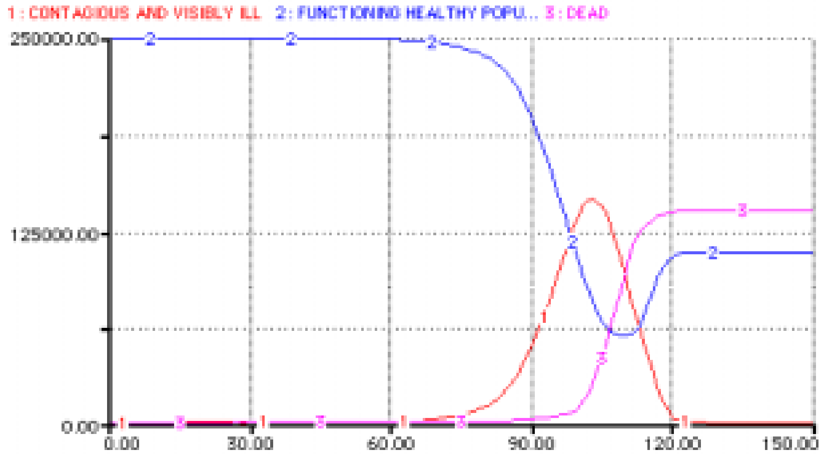


Figure 7: Projected Aztec Deaths in the Tenochtitlan outbreak of late 1521.

Altogether, upwards of half of Tenochtitlan's population died, shattering the Aztec image of invincibility not only in the eyes of the Spaniards but in those of large numbers of native peoples subjugated by the Aztec. Germs, not guns, it would appear, gained the Spaniards much needed native support for their defeat of the Aztec.

History Case Study 3 (Early Native and European Encounters in North America):

The term "genocide" has been used to describe the purposeful decimation of native peoples in the years of European settlement of North America. Yet, while the Pequot and the Huron were treated very differently by the British and the French, respectively, during the 1630s-1640s, both peoples were subject to major smallpox epidemics which preceded their annihilation. Incomplete population data in both cases renders it impossible to compare pre- and post-epidemic populations in each case. Subsequently, the question posed for the Aztec is valid too for North American native peoples: "Was it "guns" or "germs" which sealed their fates?

The model used to examine the two cases is similar to the adaptation of the generic smallpox model used to study the Aztec epidemic (see Figure 6). Here, however, the historian must solve for a different variable in each case. The Huron population prior to the smallpox epidemic was estimated to have been 40,000, but the post-epidemic population is unknown. Starting with the 40,000 and using the model (with a 30% mortality fraction for a "virgin soil" epidemic and an "added death" factor similar to that of the Aztec), it appears that fewer than 14,000 are likely to have survived the deadly disease (Fig. 8).

In the case of the Pequot, the post 1633-34 epidemic population was estimated at 3,000. This population, at the time of the Pequot War in 1637, confronted a British enemy whose total population numbered roughly 4500. How much of the Pequot population, however, had been lost to smallpox? To solve for the pre-epidemic number, all of the model variables remain as that had for the Huron (a 10% immunity fraction, 5 contacts per day, 30% mortality fraction) along with the added mortality component based on large numbers of ill. Estimated prewar populations were then selected until a post-epidemic population of 3000 was obtained. Using the model, the original Pequot population can be estimated to have been roughly 8400 (Fig. 8).

Do the population figures generated by the model provide definitive proof that germs were more powerful than guns? Yes, and no. They were likely to have been the agent through which each population was weakened prior to war. Yet in the case of the Pequot, the continuing growth of the European population sealed their inevitable fate. In effect, the epidemic hastened their demise. As for the Huron, allies of the French, it seems reasonable to assume that their opponents, the Iroquois, would not have been successful without smallpox. Their fate might have been different.

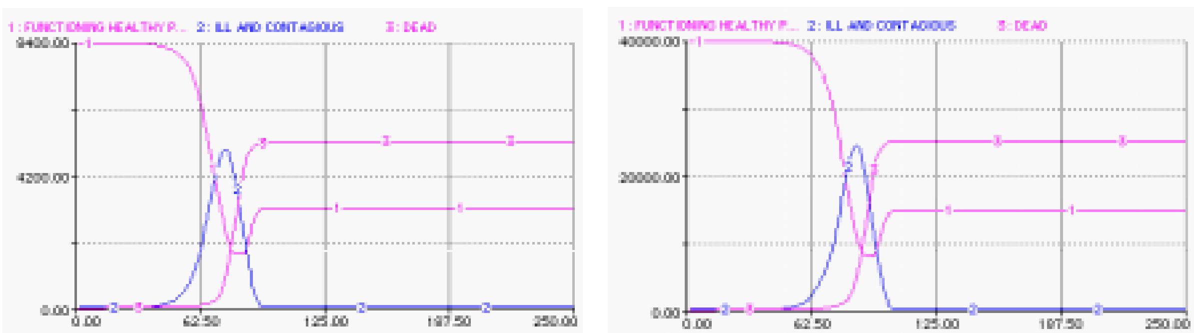


Figure 8: Model Output Suggesting the Likely Dynamics of the Pequot (left graph) and Huron (right graph) Epidemics.

Biology Case Study 4 (The Human Immune System):

As with the third biology unit, this case study uses the context of smallpox for a much larger and more generic biological theme, the dynamics of the immune system. Again, for students and teachers who are using this case study in isolation, a brief review of the basic smallpox model from Biology Case Study 2 is presented and serves as the starting point for later elements in this unit. Following that introduction, this unit:

- Presents a simplified and quite generic pre-built model of the human immune system. This simulation is designed to manipulate a number of factors: invader replication rate (how fast is the infection or cancer growing?), the leucocyte replication rate (how fast are the active players in the immune system responding?), and the effectiveness of the helper-T cells (what impact will immunosuppression, such as seen with HIV/AIDS, have on this response?). Although not specifically a model of smallpox, the default values in the simulation produce the characteristic time course of smallpox and bring the infected individual perilously close to death.

- Then moves away from the individual to a wider focus on the population. As a disease, such as smallpox, visits a population repeatedly, of the adult population become immune, so that the majority of cases move more and more into the younger ages. In essence the disease becomes primarily a childhood illness, as has happened to measles in the developed world and as happened to smallpox in Europe of the 17th and 18th centuries.

- Explores the implications of immunization as a relatively low-risk means of acquiring immunity. How do we think about the cost-effectiveness of an immunization program? What is the minimal program that can be mounted to achieve acceptable results? See Figure 9.

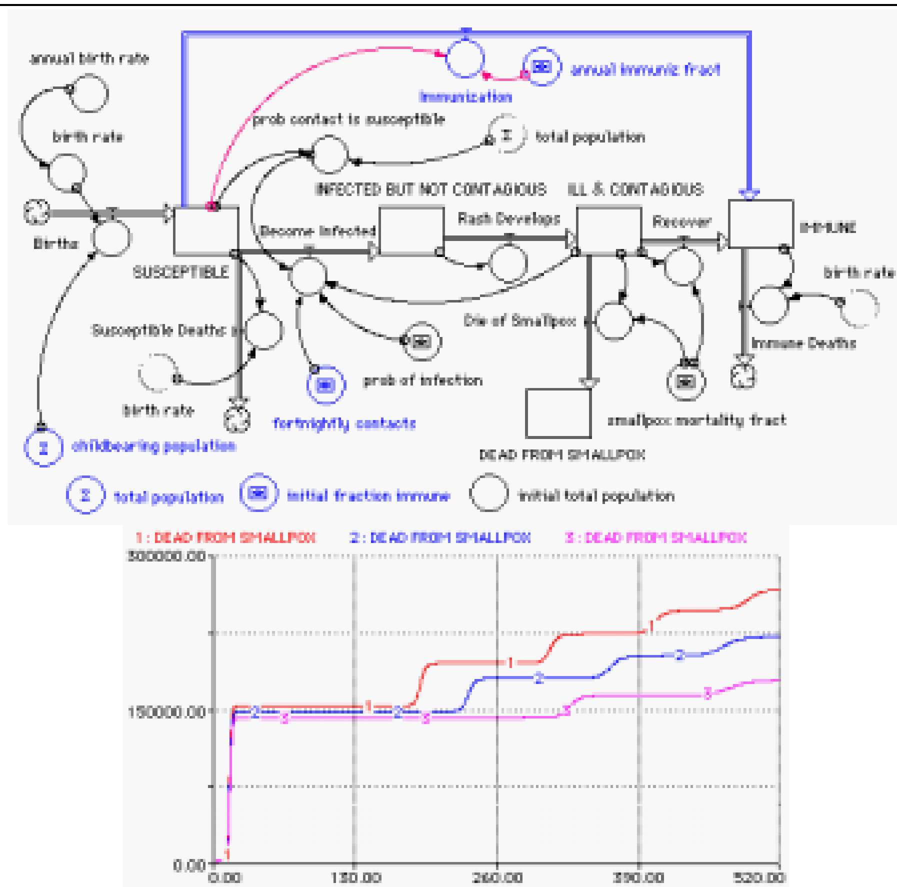


Figure 9: Model of an immunization program in Biology Case Study 4 in the History and Biology of Smallpox curricular materials. The graph represents three runs of the illustrated model: Run 1 - no immunization; Run 2 - 10% of the population immunized annually; and Run 3 - 20% of the population immunized annually. Model runs for a total of 520 fortnights (20 years).

History Case Study 4 (Smallpox in an Urban Context - London, 1675 - 1800):

For more than a century prior to the start of large scale vaccination in 1800, smallpox in London functioned as an “endemic” disease. Between 1675 and 1800, annual smallpox deaths ranged between 500 and 3500. That raises two important historical questions: What circumstances were necessary to sustain London’s experience? And second, and perhaps more importantly, how did the gradual adoption of vaccinations after 1800 impact the epidemic during the first half of the 19th century such that it both galvanized state support for mandated vaccination while concomitantly being held responsible by opponents for continued outbreaks ?

The “generic smallpox model”in Biology Case Study 2 is appropriate for addressing the pattern of endemic outbreak present between 1675 and 1800 with the following modifications:

- The addition of net migration flows into the Susceptible and Immune stocks, and
- A specified number of net immigrants per year with a portion designated as susceptible.

These modifications are essential to allow the model to capture two important dynamics: first, recognizing that deaths exceeded births in London throughout this period (1675-1800), net migration of ten thousand per year fueled the city’s growth from 400,000 to 1.1 million. A second dynamic, revealed by the model, indicates that the epidemic could only be sustained annually if roughly half the migrants were susceptible to the disease. Without this continual input of new susceptible migrants, London’s experience would likely have followed that of other communities where periodic outbreaks on 2 to 7 year cycles were followed by little if any smallpox activity.

The impact of vaccination in London (after 1800) uses the immunization model developed in Biology Case Study 4, with the addition of a net annual immigration flow of 25,000, which continued to fuel London’s growth during the first half of the 19th century, from 1.1. to 2.6 million. (see Figure 10), although birth rates during the period edged slightly above falling death rates.

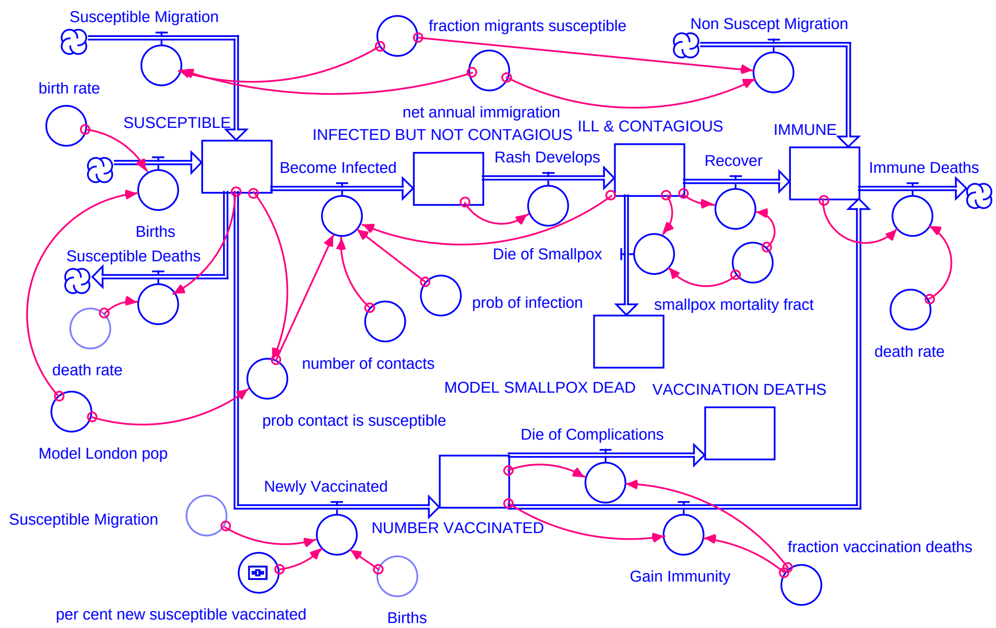


Figure 10: Vaccination in London in the Early Nineteenth Century

The impact of Edward Jenner's vaccination in London during this period, can be seen in the two graphs below. On the left is the expected rate of deaths, based on a continuation of the dynamics present between 1675 and 1800. Notice that, with larger amounts of migration and greater birth rates during the first half of the 19th century, one would expect the disease to continue to record large and, in fact, increasing numbers of annual deaths. However, with roughly half of the population of youth being vaccinated during the period, the annual rates fell from the previous half-century by more than one-third (shown of the right). Significantly, the number of deaths, which in peak years during the previous century, had ranged between 500 and 3500, never exceeded 2000, and averaged fewer than 1500 per year. That figure is particularly significant in that, at the same time as smallpox deaths were reduced, London's population more than doubled, growing from 1,096,000 in 1800 to 2,651,000 in 1850.

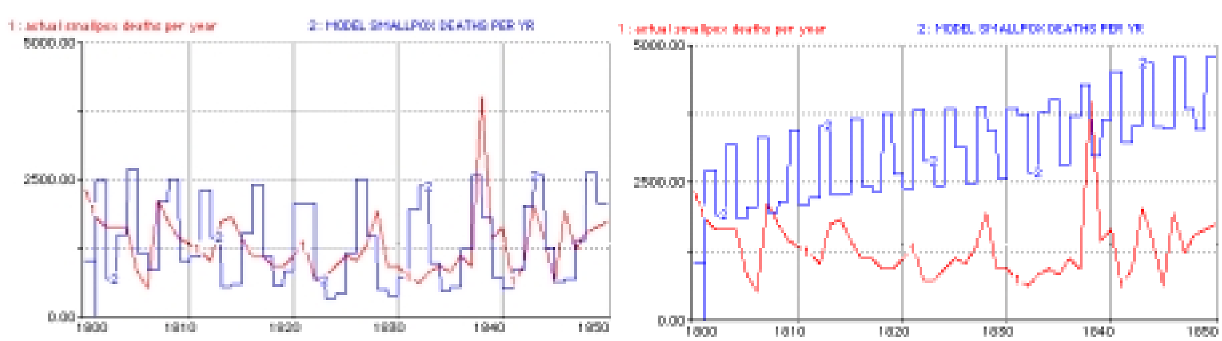


Figure 11: London Smallpox Deaths Without (Left) and With Vaccination

Yet smallpox did not disappear. While supporters of vaccination touted its positive effects and insisted that smallpox was rapidly disappearing from London's midst, opponents pointed to a major outbreak in 1838, the second most deadly in London's history, with upwards of 4,000 deaths. After this outbreak, smallpox cases once again fell until, in 1873, London experienced an even more deadly outbreak with unprecedented numbers of deaths in excess of 10,000. These irregular outbreaks, then, of what was perceived to be large proportions, reinforced the belief of many who opposed Jenner in his day and who oppose vaccinations in the present, that vaccinations were the cause of these outbreaks.

Combined Case Study 1 (The Eradication of Smallpox):

Global eradication of smallpox was visualized by Jenner, as vaccination programs were instituted during the 19th Century. While desirable, and theoretically possible, the goal proved elusive until recently. Immunization programs, as modeled in Biology Case Study 4, break the chain of infection and lead to the disappearance of smallpox in closed societies where annual immunization rates of around 35% or higher can be achieved. With the wealth, medical infrastructure, and homogeneity of developed countries, such targets were achieved; smallpox became a problem only as a concern over cases introduced from beyond the society's boundaries. Such high levels of immunization, however, proved impossible to achieve in a number of large and diverse developing countries during the World Health Organization's (WHO) effort to eradicate smallpox during the 1960's and 1970's. Given the apparent inability to dependably reach the requisite fraction of the population, WHO field workers explored another approach. When a local outbreak was discovered, resources from the mass immunization campaigns were diverted for an intense local search for those cases and a rapid, targeted effort to immunize those in closest contact with the victims. Analyses of this program are uniform in their belief that such targeted efforts were essential in stamping out the last pockets of disease, but that the mass immunization campaigns were essential precursors, in that they reduced the number of outbreaks to a level that the WHO could effectively target (e.g. Choo, undated; Fenner, 1999).

This scenario -- mass inoculation campaigns to achieve a high, but still insufficient, level of immunity, coupled with local, intense, targeted campaigns in rapid response to outbreaks -- is the focus of the primary exercise in this case study. We provide a simulation of a large developing country and challenge the students to manage their immunization resources so as to fully and finally eradicate smallpox from this population. Figures 12 and 13 St illustrate that model.

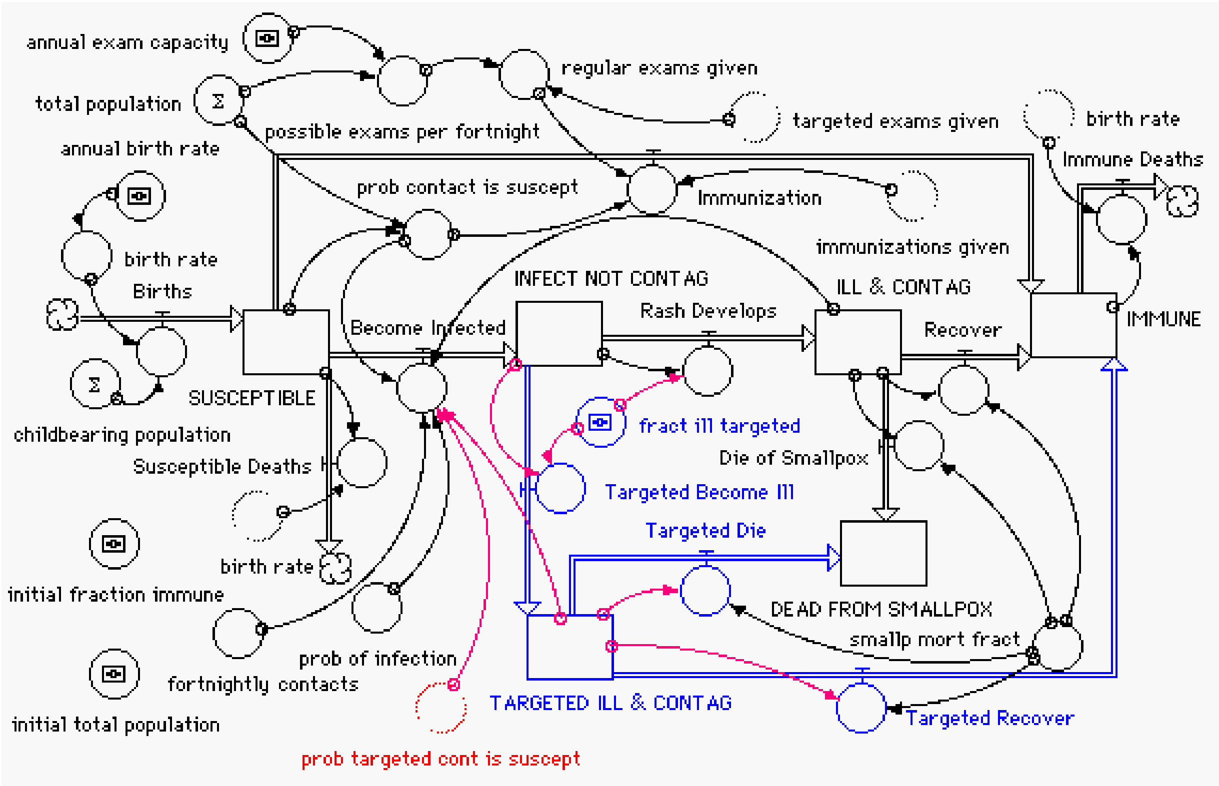


Figure 12: This model illustrates the WHO strategy for eradicating smallpox in a developing country. The model of immunization developed in Biology Case Study 4 is at the top of the figure. The stock "TARGETED ILL & CONTAG" and associated components are at the bottom and represent WHO's strategy of intense response to local outbreaks. That response reduces the "prob[ability that a] targeted cont[act] is suscept[ible]" and limits the further transmission of the disease. It comes, however, with the cost of pulling resources from the mass immunization campaign.

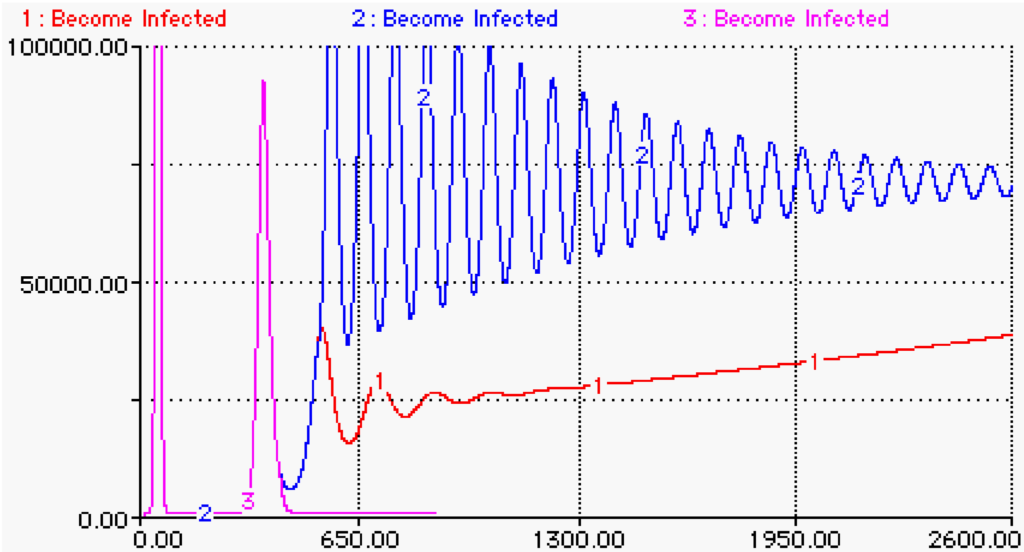


Figure 13: Three smallpox eradication scenarios; output from the model illustrated in Figure 12. In all cases the initial population is 50,000,000; the annual birth rate is 0.05 (and death rate of 0.04); initial fraction of the population immune to smallpox (from previous outbreaks) is 0.70; and the annual exam capacity (the fraction of the population that can be examined and vaccinated, if necessary, each year) is 0.25. In Run 1 no outbreaks are targeted for special attention; in Runs 2 and 3 30% of the newly infected trigger special targeted immunization programs. The difference between Run 2 and Run 3 (the poorly labeled run in which smallpox has been eradicated by 650 fortnights (25 years) is the time at which that new targeting strategy is implemented.

Combined Case Study 2 (The Threat of Bioterrorism):

The global eradication of smallpox in the 1970s marked a human triumph of unprecedented proportions. Yet, as experts now point out, the very nature of that success has led to the very real possibility that few, if any, people now possess any residual immunities to a potential terrorist strike. This raises a question: “What would likely happen were a terrorist group to release smallpox in a major American city?”

A significant amount of scholarly work has recently focused on this issue, perhaps most impressively undertaken by D.A. Henderson. This scholarship emphasizes the importance of developing an adequate supply of vaccine, training physicians to recognize the disease, and developing programs for major vaccination and quarantine programs (e.g. Garrett, 2001; Henderson, 1998).

These recommendations have been incorporated into a version of the immunization model developed in Biology Case Study 4 and modified as follows (Fig. 14):

- The model is defined to run on a daily basis;

- The differentiation of “VISIBLY ILL & CONTAGIOUS” from “ILL IN HOSPITAL” and “DIAGNOSED CASES UNDER TREATMENT” stocks, to acknowledge early delays in identification and proper quarantining treatment of the disease and the impact on numbers of contacts and disease spread;
- The vaccination flow (“Acquire Immunity”) incorporates real time lags in obtaining and real limits in initiating vaccination policy; and
- The addition of a quarantining policy for those infected but not visibly ill.

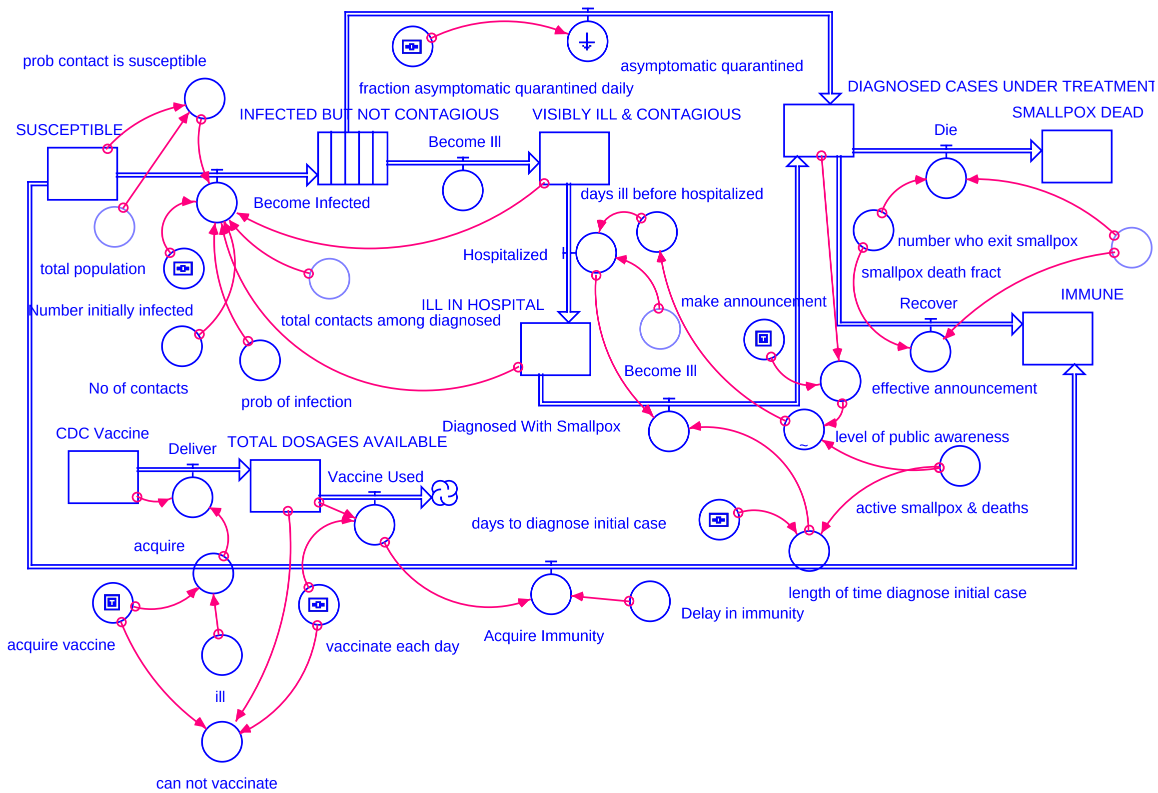


Figure 14: Bioterrorism Model

This is a particularly powerful case study insofar as it affords students the means to “experience” an attack on a day-by-day-basis, to evaluate realistic options, and to develop policy proposals for future actions to minimize the potential damage of a bioterrorist attack.

Conclusions:

This package of 10 case studies that focuses on the history and biology of smallpox was assembled for several fundamental purposes. First the material itself seemed germane to the health science, biology, and history curricula of schools; elements of this package should make significant contributions to those traditional disciplines. In addition, it provides a test for our belief and contention that education needs to move beyond such a rigidly discipline-based approach and to begin focusing on real-world issues that require a cross- or inter-disciplinary approach; this package is meant to provide like-minded educators with a set of materials to support one such exploration. This package also provided us a chance to develop for pre-college education a set of materials that builds a framework for student learning on a foundation of systems thinking and dynamic modeling. Finally, this integration of 10 cases is meant to serve as an initial effort to develop a template for the construction of additional such packages.

These materials are not yet extensively tested. We welcome, indeed we require, feedback from both the K-12 educational community and the system dynamics community to help us evaluate how well we have achieved these ambitious goals and how and where we can improve upon our efforts as we move forward with further efforts.

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