"Developing a theory of the societal life cycle of cigarette smoking"

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Abstract

Background. *Cigarette smoking presented the most significant public health challenge in the United States in the 20th Century and remains the single most preventable cause of morbidity and mortality in this country.*

Method. *A number of System Dynamics models exist that inform tobacco control policies. We reviewed them and discuss their contributions. We developed a theory of the societal life cycle of smoking, using a parsimonious set of feedback loops to capture historical trends and explore future scenarios.*

Results. *Previous work did not explain the long-term historical patterns of smoking behaviors. Much of it used stock-and-flow to represent the decline in prevalence in the recent past. With noted exceptions, information feedbacks were not embedded in these models. We present and discuss our feedback-rich conceptual model and illustrate the results of a series of simulations. A formal analysis shows phenomena composed of different phases of behavior with specific dominant feedbacks associated with each phase. We discuss the implications of our society's current phase and report simulations of what-if scenarios.*

Conclusion. *Our theory suggests that it is essential to maintain a high level of awareness, artificially, regarding the health consequences of smoking, because awareness deteriorates to the extent that society succeeds in minimizing cigarette smoking. We extend this model-based insight to policy implications dealing with mandating warning labels or granting "reduced risk" approvals. We draw three additional policy implications from this work, including the need to monitor the level of awareness, particularly for those coming of age.*

Introduction

Cigarette smoking presented the most significant public health challenge in the United States in the 20th Century and remains the single most preventable cause of morbidity and mortality. According to a recent study by the Centers for Disease Control and Prevention (CDC), more than 400 thousand premature deaths attributable to smoking occur annually (years of potential life lost were estimated at approximately 5.1 million and productivity losses at $96.8 billion annually).[1] One in every five U.S. adults is still smoking.[2] While we continue to struggle with this problem, other countries are not faring much better and cigarette smoking is actually on the rise in some places.[3]

Figure 1 depicts the pattern for annual consumption of manufactured cigarettes in the United States between 1900 and 2006. The peak in cigarette smoking occurred in the 1960s, and dropped sharply since, presumably due to increased awareness of the harmful effects of smoking and successful tobacco control initiatives.

< Figure 1 >

The purpose of this research is to explain this historical pattern of behavior using a parsimonious feedback-rich model, and to be able to anticipate future trends that take into account the system structure underlying this pattern. Our effort is focused on conceiving the structure needed to explain historical smoking behaviors at the population level and, thus, to develop an endogenous theory of the societal life cycle of cigarette smoking that is generally applicable.

Working with a structural theory, we should be able to anticipate future trends. Will cigarette smoking continue to decline, level off, or actually rise again? With a model depicting an appropriate "governing structure" of smoking and tobacco control, we can realistically analyze plausible future scenarios, and evaluate strategies that can effectively influence system behavior.

We explore the population responses to changes in the system, as well as the time frame for the changing patterns of behavior resulting from policy implementation and social adaptation. Our population of interest is the USA; however, a general theory should have applicability to other settings if it adequately depicts the social phenomenon of cigarette smoking.

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[1] http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5745a3.htm
[2] http://www.infoplease.com/ipa/A0762370.html
[3] http://www.wpro.who.int/media_centre/fact_sheets/fs_20020528.htm

Review of previous models

Because we are interested in capturing the structure of the cigarette smoking and tobacco control system that incorporates a feedback-rich perspective, existing System Dynamics models were an obvious point of departure for our study. An initial broad search of the literature led us to review the following works:

- The MIT model (Roberts *et al.*, 1982).
- The Tobacco Policy Model – TPM (Tengs *et al*., 2001a; Tengs *et al*., 2001b; Tengs *et al*., 2004; Ahmad, 2005a; Ahmad, 2005b; Ahmad and Billimek, 2005; Tengs *et al*., 2005).
- The Initiative on the Study and Implementation of Systems – ISIS Model (Richardson, 2007).
- The New Zealand TPM (Cavana and Tobias, 2008; Tobias *et al*., 2010).
- The Prevention Impacts Simulation Model – PRISM (Homer *et al*., 2008; Hirsch *et al*., 2010; Homer *et al.*, 2010).

We reviewed this work primarily based upon publications in peer-reviewed journals and, in one case, a monograph (ISIS). We were able to obtain and look into some of the models (ISIS, NZ-TPM, and PRISM) with the intent of understanding the structure behind these models to incorporate key features into our work.

The MIT model

The MIT model was set up using U.S. smoking population data between 1965 and 1974. For the purpose of analysis, the simulations started in 1970 and ran for a period of 40 years, until 2010. The results show declining prevalence. Some forms of feedback were incorporated into the model, such as reinforcing feedback due to peer pressure and balancing feedback due to perception of hazards associated with smoking. The authors used the model to examine strategies such as anti-smoking campaigns, increased prices of cigarettes, reduction in contaminants, and advertising bans (both marketing and education). They found model behavior to be very sensitive to model assumptions, considered at the time highly uncertain.

The authors did not address the historical behavior leading to the peak in cigarette smoking. They only examined the period of decline in smoking prevalence starting in the mid 1960s.

The Tobacco Policy Model (TPM)

The Tobacco Policy Model was calibrated using U.S. smoking population data from 1995 to 2003. For the purpose of analysis, the simulations started in 2001 or 2003 and ran for a period of 50 years or more. (In some publications the unit of analysis was not the U.S.

population, but that of the state of California.) No form of information feedback was incorporated in the model except for first-order controls for the population stocks. However, the model has a very elaborate stock-and-flow structure, capturing six age groups per gender and distinguishing three categories: never smokers, smokers, and former smokers. The model contained physical feedback, in the form of “relapse” from former to current smokers, in addition to initiation and cessation flows.

The authors used the model to contrast the impacts of changes in initiation, cessation and relapse, and to examine strategies such as education, reduced harm (both toxicity and nicotine level), reduced access to cigarettes, and increased prices due to higher taxes. Their analyses showed steady declines in prevalence, and great effort was directed to estimating the decline that could be achieved with each strategy examined, as well as to measuring costs. An interesting aspect of this work was the computation of Quality-Adjusted Life Years (QALYs) to measure cost-effectiveness.

The authors did not explain the long-term historical behavior. They looked only at the very recent period of decline in smoking prevalence. While the model provides useful forecasts based upon the ongoing behavioral trend, without information feedback it cannot endogenously capture changes in behavioral trends.

The ISIS model

The ISIS Model was calibrated using U.S. smoking population data from 1965 to 2000. For the purpose of analysis, the simulations ran for a period of 55 years, until 2020, contrasting model behavior with historical data for selected variables between 1965 and 2000. In general, the simulations suggested a further decline in prevalence. This model was built with emphasis on information feedback. Similar to the MIT model, it contains a reinforcing feedback of smoking as a social norm (aka, peer pressure), and a balancing feedback due to public awareness of tobacco health risk (aka, perceived hazards of smoking).

This effort did not include explanation of the historical behavior leading to the peak in cigarette smoking in the 1960s. Instead, the model was used to illustrate the use of System Dynamics for tackling a complex problem embedded in a feedback-rich system. Less emphasis was placed on examining tobacco control strategies and scenarios.

The New Zealand TPM

The New Zealand Tobacco Policy Model was calibrated using New Zealand smoking population data from 2001 to 2004. For the purpose of analysis, the simulations started in 2001 and ran for a period of 30 to 50 years. The only form of information feedback incorporated in the model was a reinforcing effect involving role modeling, similar to the notion of peer pressure or social-norm formation. (Instead of first-order control on population stocks, this model used a conveyor-belt or material-delay formulation.) This model is very similar in scope to the U.S. TPM model, relying on an elaborate stock-and-flow structure. It includes the additional population health effects of second-hand smoking. Similar to the TPM approach, the authors examined strategies involving harm reduction (both toxicity and nicotine level), and increased prices. Their analyses had an impact on resource allocation, leading to a governmental decision to invest US$32 million in cessation services.

The authors did not explain the historical behavior, calibrating to what we presume to be the period of decline in smoking prevalence in New Zealand. Without emphasis on information feedback, the model cannot endogenously capture changes in behavioral trends. Thus, the simulations showed continued decline in prevalence.

The Prevention Impacts Simulation Model (PRISM)

The Prevention Impacts Simulation Model was calibrated using U.S. population data from 1990 to 2004. For the purpose of analysis, the simulations ran for a period of 50 years, until 2040. (There are also instantiations of this model for specific counties in the states of Texas and Colorado.) This model focuses on the contributions of cigarette smoking to cardiovascular disease. Therefore, it includes smoking as one important factor. No form of information feedback was incorporated in the smoking sector of the model (except for first-order controls on the population stocks). However, the model accounts for long-term ex-smokers, who have a reduced relative-risk of morbidity and mortality, and includes second-hand smoking. Great care was directed towards estimating morbidity and mortality, and to assessing health care capacity needed to meet increased demand for public health services. Their analyses suggested a further decline in smoking prevalence, particularly with the implementation of policies that promote environmental changes and healthy lifestyles.

The authors' purpose was not to explain the long-term historical behavior in per capita cigarette consumption. Thus, they accounted for the very recent period of decline in smoking prevalence. However, without incorporating information feedback, this model cannot endogenously capture changes in trends.

In Summary

Table 1 illustrates the choice of time horizon of interest for each of these studies, as well as for this study. The existing SD work did not examine the historical growth in cigarette smoking behaviors, but was informative in:

1. Providing a foundation upon which to identify system structures, determine morbidity and mortality, assess potential impacts of interventions and measure their cost effectiveness.
2. Demonstrating impact in decision making and influencing public health policy.
3. Providing insight on key information feedbacks, such as:

- The reinforcing feedback between prevalence and initiation rate.
- The balancing feedback due to awareness of health consequences of smoking.

All of the models that we reviewed looked at a relatively short historical period of reference, and none of the models looked at the possibility of a “rebound” in smoking behaviors, which is one of the important scenarios for our study. Therefore, we saw a path open to expand this body of knowledge. Our research effort was focused on developing the structure needed to account for entire societal life cycle of cigarette smoking, with emphasis on information feedback and using an Occam’s razor approach. This is similar to what Forrester did in his study of urban dynamics (Forrester, 1969). In order to examine the problem of urban decay, he developed a theory of urban growth.

Dynamic hypothesis

In Figure 2, we illustrate a conceptual model, which presents our parsimonious, feedback-rich theory of the societal life cycle of smoking.

< Figure 2 >

We incorporated the major feedbacks used in the existing studies:

- Loop 1 is a reinforcing loop that represents peer pressure, social norm formation, or role modeling. We call it the “initiation” loop.
- Loop 2 is present in the stock-and-flow structure of all of the models examined. We call it the “cessation” loop because it captures the balancing effect of changes in prevalence due to cessation.
- Loops 3 and 4 are balancing loops that represent the perceived hazards of smoking or awareness of tobacco health risks. They act to influence initiation and cessation, respectively; “awareness curbs initiation” and “awareness boosts cessation.”
- But, we included a novel loop 5, which we defined as the “losing awareness” loop.

In our model, awareness of health consequences does not represent cumulative scientific knowledge but, rather, the level of awareness in the mindset of the population of interest. The notion of “forgetting” is intended to capture intergenerational gaps and “time to forget” is set to 35 years. Of course, if awareness is somehow institutionalized (e.g., graphic warning labels in cigarette packages), this parameter will also represent the de-institutionalization of tobacco control measures.

This model is abstract, designed to serve as prototype for our theory. It is intended as proof of concept. It closely resembles the well-known structure of the Yeast Population model (Mojtahedzadeh, 2008). There are no actual people in the model. Even though we use it to represent century-long phenomena, the model does not represent births, aging, or deaths.

The algebraic relationships are very simple and the parameters are notional, as documented in Appendix 1.

Calibration

We calibrated the model to roughly replicate the shape of the cigarette per capita curve while overlapping as closely as possible the data for smoking prevalence. Both sets of data and the simulated behavior (base run) are shown in Figure 3.

< Figure 3 >

Our goal was not to have a realistic model or valid simulation, but to underscore the role of the time horizon and information feedback in explaining the historical smoking behavior in the population and in capturing tipping points endogenously.

Note that there are two scales in the Y-axis. Also, our time-series data for cigarette smoking prevalence is incomplete, going back to 1970 only. Finally, we observe that a greater percentage of the population smoked in the past and, those who smoked consumed more cigarettes per year.

Formal analysis

We used pathway participation metrics to conduct formal model analysis and trace model behavior to model structure (Mojtahedzadeh, 1997). The implementation was done using *Digest* (Mojtahedzadeh *et al*., 2004). We identified four phases of behavior, each dominated by a different feedback loop, as illustrated in Figure 4.

< Figure 4 >

Phase 1, unconstrained growth, is dominated by the reinforcing “initiation” loop. The Great Wars and the Great Depression are noise in an otherwise smooth exponential growth pattern. Since these influences are not in the model, the simulated behavior does not capture those fluctuations. The transition to the next phase occurs in the mid- to late-1940s.

In *phase 2*, awareness of health effects from smoking curbs and reverses the initial growth trend. This phase is dominated by the balancing “awareness curbs initiation” loop. Note that the specific events are not exogenously captured in the model; rather, the model endogenously simulates the awareness process. In this light, the Surgeon General’s Report, for example, can be seen as a manifestation of the state of awareness in society, as well as an element of the structural drive for behavioral change. Coincidently or not, the report publication coincides exactly with the tipping point of cigarette consumption behavior, preceded by the scientific evidence of the link between smoking and cancer, consolidating and boosting public awareness, and followed by the first significant tobacco control initiative, the broadcast ban on cigarette advertisements.

The next phase begins in the mid- to- late-1980s. During *phase 3*, the system is deflated. The dominant loop here is the balancing "cessation" loop. Awareness has an impact on cessation, but because cigarette smoking is addictive, the boost effect of awareness on cessation has limited impact. (The latter is the only feedback loop that is never dominant.) Additional tobacco control measures maintained the spotlight on the cigarette-smoking problem. However, initiation had already declined drastically in the previous phase, and nicotine addiction prevented a significant increase in cessation in this one. Still, with cessation greater than initiation, prevalence continued to fall, albeit more slowly.

According to this analysis, we recently entered *Phase 4*, which is dominated by the balancing loop of "loosing awareness." We appear to be in the beginning of a very long phase that could last almost 70 years. During this time, scientific knowledge is not lost, but smoking as a health issue loses the spotlight because prevalence is relatively low and continues to decline for another 30 years or more. Naturally, over this time period other population-health challenges, such as obesity for example, will gain prominence, visibility and resources. Eventually, initiation will become greater than cessation again, around 2050. The analysis indicates the beginning of a new cycle after 2070 when exponential growth resumes.

The exact transition dates should not be given too much weight. However, it is interesting to note the possibility of a new life cycle, albeit one that will not begin for several decades. This system is characterized by damped oscillations; therefore, the next peak should be much lower and the behavior tends toward stability, when awareness is institutionalized at some level.

What-if scenarios

We examined interventions to this system using four what-if scenarios:

1. What happens if we reduce initiation?
2. What happens if we increase cessation?
3. What if we "lose focus?"
4. What if we "maintain awareness?"

A reduction in initiation could be implemented by restricting access to cigarettes for those aged 21 and younger. An increase in cessation could be implemented by providing free nicotine replacement therapy (NRT) and behavioral counseling. Time to forget the health consequences of cigarette consumption might decrease if the issue of smoking loses the public-health spotlight; conversely, permanent measures may be taken to maintain awareness –even if prevalence were to become negligible and other health issues much more prominent.[4]

Predicated on all of these changes being implemented in 2011, the results of these simulations, contrasted with the base run, are shown in Figure 5:

< Figure 5 >

Emphasizing programs that reduce initiation and/or increase cessation can achieve further reductions in cigarette consumption. However, the balancing feedback loops that go through awareness of health consequences counteract such efforts. To the extent that we are successful in reducing smoking prevalence, awareness falls in the long run and this causes initiation to rise and cessation to fall, resulting in a similar pattern for prevalence as observed in the base run.

The quantity, time to forget the health consequences of cigarette consumption, has an important role in determining the dampening property of the oscillation. If we lose focus (shorten the time to forget), the new cycle begins sooner and the rise in prevalence is more pronounced. Therefore, maintaining a high level of awareness is critical to keeping prevalence low in the population. This awareness must be maintained despite success in reducing smoking prevalence. In fact, the more successful the reduction of smoking prevalence, the greater the effort must be in maintaining awareness; otherwise, the importance of non-smoking will fade from public consciousness.

The ability to keep prevalence in decline depends upon the net difference between initiation and cessation rates. So long as cessation is greater than initiation, prevalence will continue to decline. This can be achieved by multiple means. Closely monitoring these rates of change, as opposed to simply tracking prevalence, can provide an early warning signal of a reversal in the prevalence trend.

Policy implications

Warning labels and other forms of institutionalization

As of today, we enjoy a high level of public awareness of the health consequences of smoking. This helps individuals make informed choices about initiation and cessation. However, our analysis suggests that it is essential to maintain a high level of awareness artificially, because it will deteriorate to the extent that we are successful in minimizing cigarette smoking. Mandating warning labels on cigarette packages, particularly those with

[4] We can also test the effects of strategies that impact the elasticity of initiation or cessation. Reducing cigarette addictiveness, for example, should increase the elasticity of the effect of awareness on cessation. It will be easier to quit, if cigarettes are less addictive.

graphic pictures, is helpful to raise awareness in young individuals who are considering initiating. Legislation solidifies social norms and makes them harder to reverse. In this sense, barriers and restrictions may help increase "time to forget" such that, taken together, these measures are effective in maintaining awareness for future generations.

Use surveys to monitor awareness

A direct means to know if awareness is deteriorating over time and across generations is to measure it. It will be especially informative to ask teenagers what they know about the pros and cons of smoking, and where they obtain their information. If we find that awareness regarding the health consequences of cigarette smoking is falling over time, we can anticipate that smoking prevalence will likely rise in the near future. Such surveys can help determine when to allocate additional resources toward tobacco control. When the level of awareness is already high, it may be more efficient to put scarce health resources into fighting other public health challenges.

Account for possible impact of "reduced risk" approvals on awareness

Current legislation allows the possibility of approving reduced-risk labels for new products. This can subtract from general awareness, or create a cloud of misinformation; even when specific products are indeed reduced risk. Consider electronic cigarettes, for example, they may not have as many harmful ingredients and they may not cause second-hand smoke. They may be allowed in social environments where traditional cigarettes have been banned, increasing social tolerance. The image of someone smoking may regain acceptance. Their negative consequences may be greater to the extent that smokers decide against quitting. E-cigarette smokers may become dual users, reducing their traditional cigarette consumption but not eliminating it.

Assess health consequences of (new) products and inform the public

A more informed approach than labeling a product reduced risk is to mandate that all products carry a label specifying their known risks and any uncertainty due to factors yet unknown). These labels would have to be updated regularly to reflect the best scientific knowledge about their impact upon consumers.

Set a target for the level of prevalence

Albeit dysfunctional due to the long time delay, it is in the nature of the system to be self-correcting. Resources devoted to reducing initiation, increasing cessation, promoting and institutionalizing awareness offset future societal costs associated with the health consequences of tobacco consumption. This equation requires balancing short-term versus long-term tradeoffs. Setting "realistic" targets would be helpful to avoid sliding goals. Short-term success may result in long-term failure. This begs the question regarding what amount of effort is satisfactory and sustainable over the long haul?

Measure rates of change (initiation and cessation) as opposed to accumulation (prevalence)

Finally, while this may be obvious, it is essential to recognize that smoking prevalence is a composite measure. It is an accumulation that results from the inflows and outflows associated with initiation and cessation respectively. Measuring and understanding trends in initiation and cessation would provide better indicators of tendency, than looking at annual fluctuations in prevalence. It would also help target resources to the side of the equation that is trending unfavorably. These measurements should control for age, gender, ethnicity, social economic status, and social-networks, to identify pockets of high infection and contagion. This detailed level of monitoring and understanding may significantly improve efficiency in allocating scarce prevention and treatment resources.

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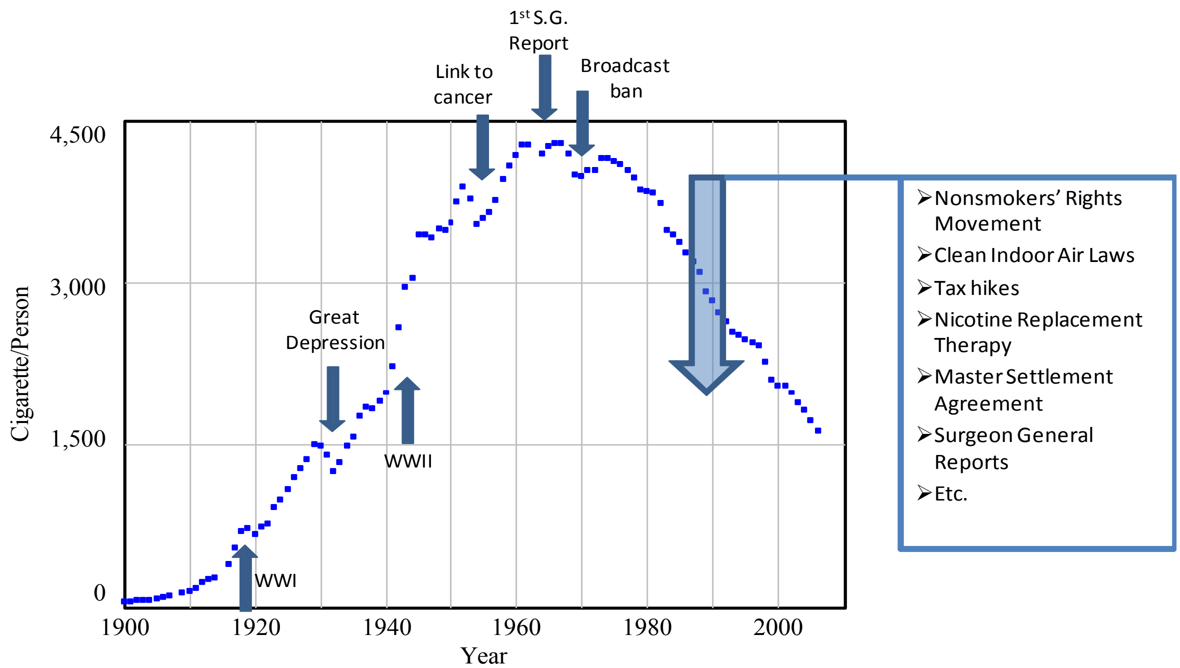
Appendix 1 – Model equations

Awareness of health consequences = INTEG (Learning-Forgetting, Initial K); Units: Dmnl
Cessation = Smoking prevalence*Cessation rate; Units: 1/Year
Cessation rate = Initial CR*Effect of NB on cessation; Units: 1/Year
Effect of NB on cessation = Net benefit^(-Elasticity of cessation); Units: Dmnl
Effect of NB on initiation = Net benefit^Elasticity of initiation; Units: Dmnl
Elasticity of cessation > 0; Units: Dmnl
Elasticity of initiation > 0; Units: Dmnl
Forgetting = Awareness of health consequences/Time to forget; Units: 1/Year
0 < Initial CR < 1; Units: 1/Year
0 < Initial IR < 1; Units: 1/Year
0 < Initial K < 1; Units: Dmnl
0 < Initial P < 1; Units: Dmnl
Initiation = Smoking prevalence*Initiation rate; Units: 1/Year
Initiation rate = Initial IR*Effect of NB on initiation; Units: 1/Year
Learning = Perceived health consequences; Units: 1/Year
Net benefit = Perceived benefits from smoking-Awareness of health consequences; Units: Dmnl
Perceived benefits from smoking = 1; Units: Dmnl
Perceived health consequences = Smoking prevalence/Time to manifest health consequence; Units: 1/Year
Smoking prevalence = INTEG (Initiation-Cessation, Initial P); Units: Dmnl
Time to forget ~ 35; Units: Year
Time to manifest health consequence ~ 25; Units: Year

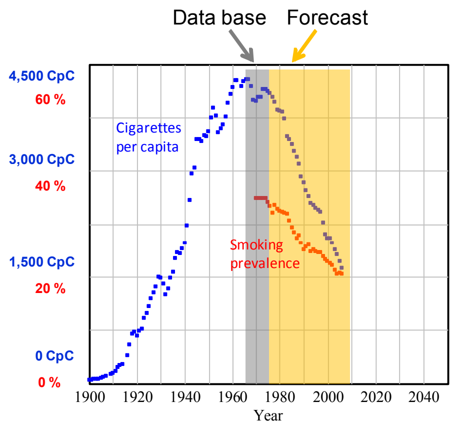
Figure 1. Annual consumption of manufactured cigarettes per adult
(United States, 1900-2006)



Source: http://www.cdc.gov/tobacco/data_statistics/tables/economics/consumption/

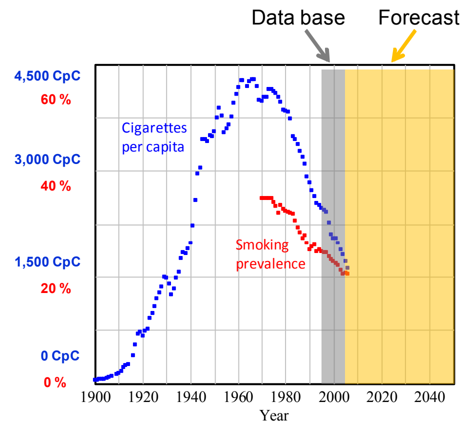
Table 1. Choice of time horizon for SD studies of cigarette smoking and tobacco control

MIT model



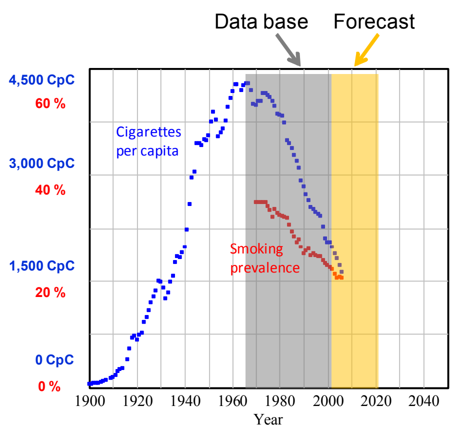
Hindsight (1965-1974); foresight (until 2010)

Tobacco Policy Model



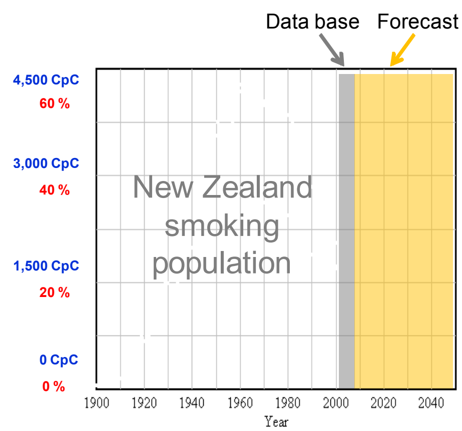
Hindsight (1995-2003); foresight (until 2051+)

ISIS model



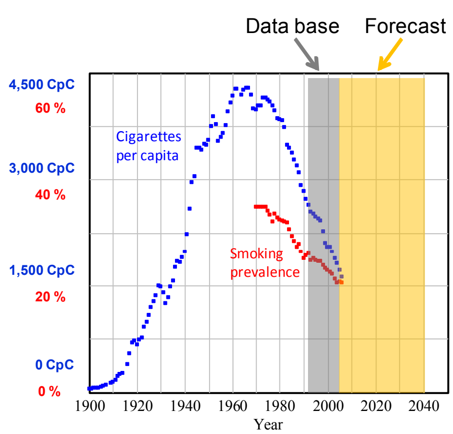
Hindsight (1965-2000); foresight (until 2020)

New Zealand TPM



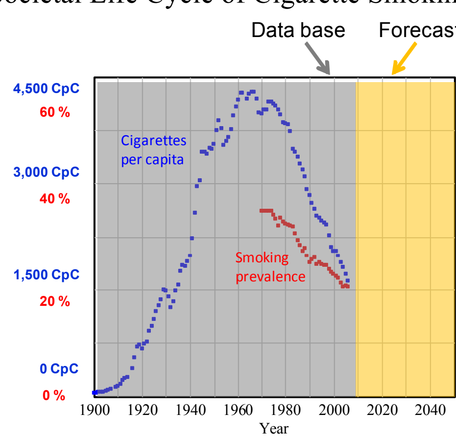
Hindsight (2001-2004); foresight (until 2051+)

PRISM



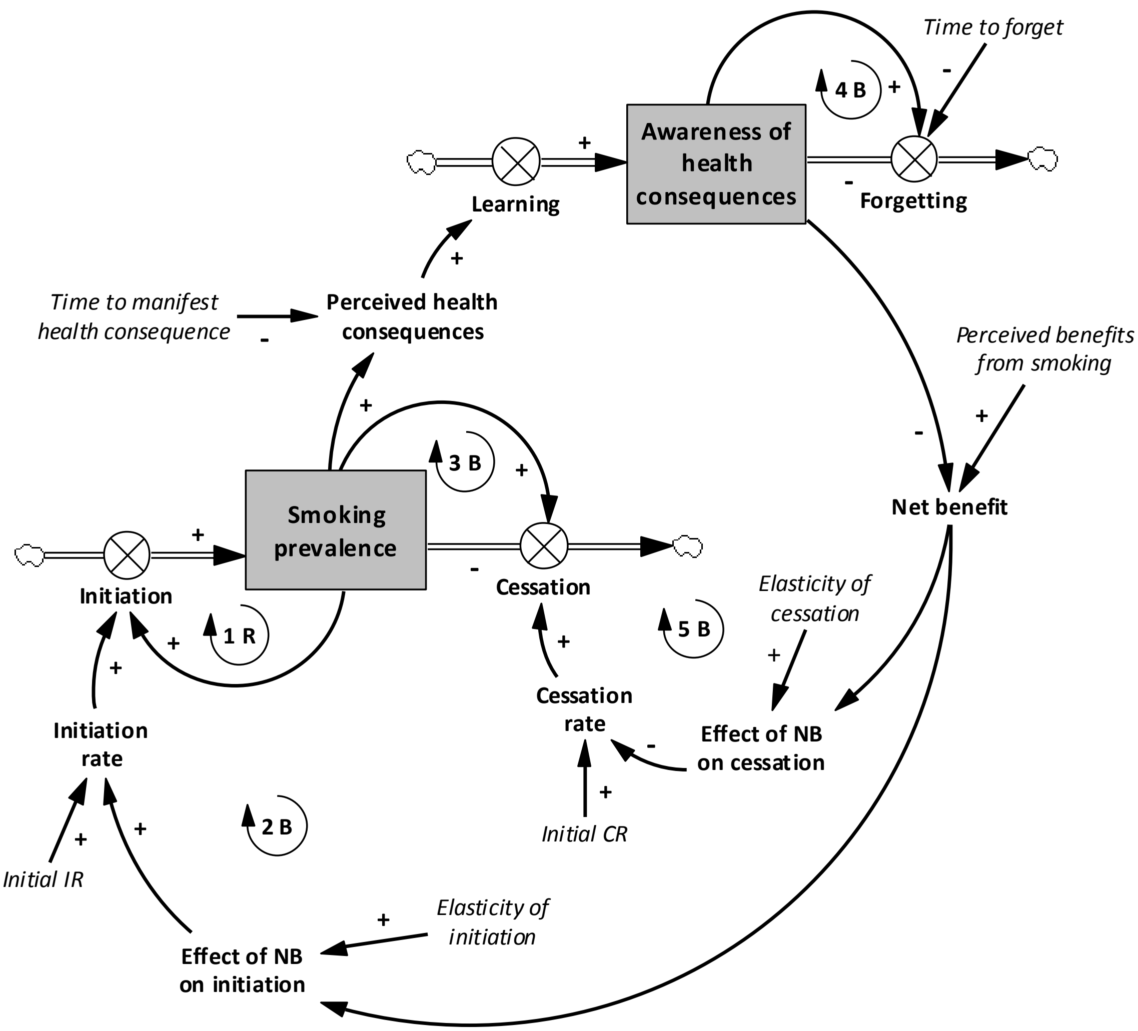
Hindsight (1995-2003); foresight (until 2040)

Societal Life Cycle of Cigarette Smoking



Hindsight (1900-2010); foresight (until 2051+)

Figure 2. Our parsimonious theory of the societal life cycle of cigarette smoking



Feedback loops:

1. "Initiation" (reinforcing)
2. "Cessation" (balancing)
3. "Awareness curbs initiation" (balancing)
4. "Awareness boosts cessation" (balancing)
5. "Losing awareness" (balancing)

Figure 3. Base run (historical)

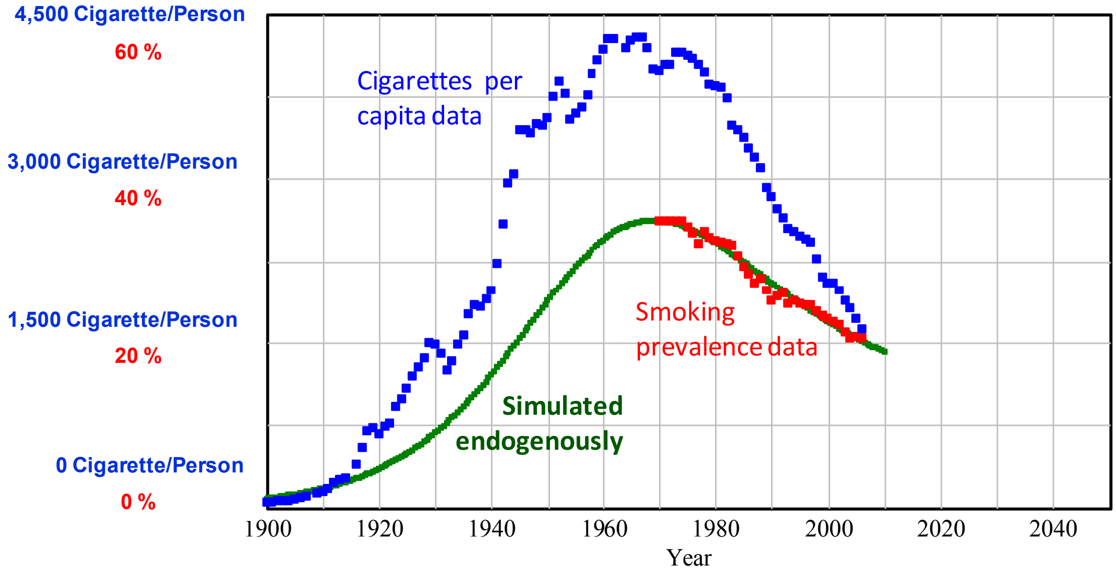


Figure 4. Societal life cycle of cigarette smoking

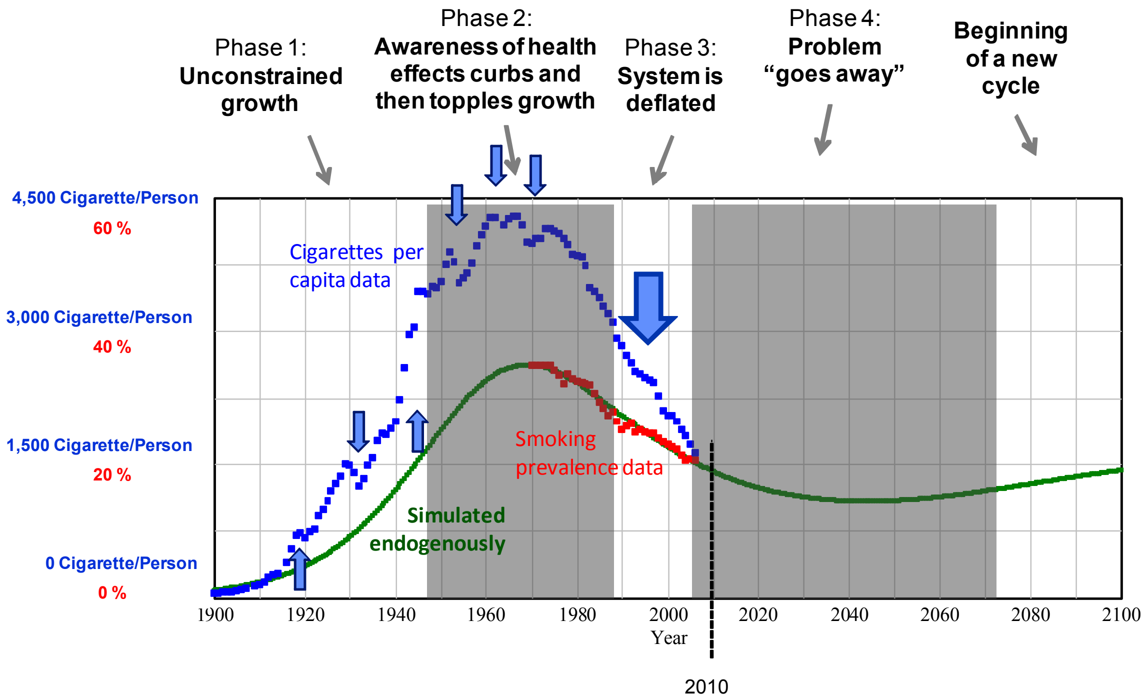


Figure 5. Four what-if scenarios