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Obesity Population Dynamics: Exploring Historical Growth and Plausible Futures in the U.S.

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Abstract

A system dynamics simulation model was developed for understanding trends in obesity in the United States. Data on population body weight from 1971-2002 were combined with information from nutritional science and demography into a single analytic environment for conducting simulated policy experiments. Interventions among school-aged youth and others were simulated to learn how effective new interventions would have to be to alter obesity trends; which population subsets ought to be targeted; and how long it takes for those actions to generate visible effects. One finding is that an inflection point in the growth of overweight and obesity prevalences probably occurred during the 1990s. Another is that new interventions to assure caloric balance among school-age children—even if very effective—would likely have only a relatively small impact on the problem of adult obesity. More comprehensive efforts at all ages are needed to avoid the high costs and heavy burden of disease due to adult obesity.

Understanding Obesity as a Dynamic Problem

In February 2005, the U.S. Centers for Disease Control and Prevention (CDC) organized the Trailblazer Team on Overweight and Obesity Prevention, which intensified efforts to articulate and pursue a national strategy for assuring the conditions in which all people can maintain a healthy weight at every stage of life. Agency staff and invited collaborators from across the country participated in a facilitated process to develop a more formal understanding of obesity dynamics in the U.S. The group reviewed data on the rise of overweight and obesity prevalence over the past decades, along with numerous trends in social and physical conditions that have altered people's food and activity choices. The project's purpose was to learn about the conditions that have driven population weight gain in the past, as well as how to direct future trends in a safer, healthier direction.

Participants recognized from the outset the need for a comprehensive and dynamic view of the obesity challenge. A large number of potential influences were considered, consistent with the ecological view recommended by the Institute of Medicine (IOM 2005). These are summarized in Figure 1, adapted from the IOM framework, which organizes forces that affect people's energy balance into four overlapping spheres representing individual factors, behavioral settings, sectors of influence, and social norms and values.

Even with such a broad array of potential influences, many questions remain about how much and how quickly national levels of overweight and obesity can be reduced given the rate of their past and current growth. To address such questions about population dynamics, the group developed a formal system dynamics (SD) simulation model. Available time series data on population weight were combined with information from nutritional science, energy regulation research, and demography into a single analytic environment suitable for conducting simulated policy experiments. In particular, the model described below helps users address three questions that are critical for developing sound action plans and setting justifiable health impact goals:

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- How effective would new interventions have to be to make a meaningful difference in the trajectory of overweight and obesity prevalence?
- Which subsets of the population ought to be targeted?
- How long it will take for those actions to generate visible effects?

Perhaps the most active area of current policy discourse for obesity prevention focuses on interventions for school-age youth (IOM 2005). Various proposals have been advanced to reform school policies, parenting styles, advertising, marketing, media, taxes, agriculture, health care services, neighborhood design, and more. In this paper, we report the results of selected simulated experiments designed to explore the impact of interventions among school-aged youth (and others) on obesity levels over the life-course.

The purpose of studying these scenarios is not to predict future levels of obesity, but rather to learn how the direction of obesity trends may plausibly change under different configurations of action or inaction. Without such tools, one is left with a process in which the analysis of the impacts of policy alternatives tends to be fragmented, static, and unsystematic, potentially reaching conclusions that overlook important sources of inertia and resistance that are features of all complex systems (Sterman 2006, Homer and Hirsch 2006).

Historical Trends

Data on population fractions of overweight, obese, and severely obese for the period 1960-2002 are displayed in Table 1 and Figure 2. This information comes from the National Health and Nutrition Examination Survey (NHANES, 1971-2002) and its predecessor, the National Health Examination Survey (NHES, 1960-1970) (CDC/NHANES 2006). The more detailed NHANES data were assembled by staff at the CDC's National Center for Health Statistics, based in some cases on ad-hoc analyses performed for the purposes of our project. A close look at the historical trends provides a first impression of what future may be likely. In particular, the data show that the prevalences (as a fraction of the population) were essentially flat through the 1971-1974 survey, accelerated through the 1988-1994 survey, and then grew at the same or slower rate through the 1999-2002 survey. Given a history that has already included a period of accelerating growth followed by no further acceleration, one might reasonably expect that—in line with other S-shaped growth phenomena—we will soon enter (if we have not already entered) a period of decelerating growth.

A basic tenet of SD modeling is that a model should allow for multiple plausible trajectories of change, including S-shaped growth. It should not assume *a priori* that the future will be a simple continuation of the past. With the inclusion of model inputs that can simulate the effects of changing interventions over time, our model is capable of yielding a variety of plausible patterns of both growth and decline.

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Formulating the Obesity Dynamics Simulation Model

Several criteria guided the formulation of the obesity dynamics model. It was designed to

- build upon the best information available;
- use knowledge of past trends to anticipate a plausible "status quo" future, in which it is assumed that no new interventions are introduced;
- compare that status quo future against one or more alternative futures modified by different types of interventions, either alone or in combination, including those that vary by age, sex, or category of body mass index (BMI, defined as the ratio of weight in kilograms to the square of height in meters);
- trace the consequences of those interventions decades into the future to assess the timing and cumulative magnitude of their effects, and
- allow diverse stakeholders to develop a more comprehensive understanding of the population dynamics of BMI, as well as the most plausible gains that health protection efforts can deliver.

Scope and Structure

The obesity dynamics model is a tool for conducting controlled, simulated experiments that take into account key features of the population dynamics of body weight. Fundamental among these is the fact that changes over time in an individual's weight have a systematic character and are not arbitrary or random. At a population level, the implication is that prevalences of overweight and obesity are "carried over" from one age to the next over the life-course. This carry-over effect constrains the rate at which overall population prevalences can change.

After iteratively developing models of varying size and scope along with the development of hypotheses and supporting evidence (Homer 1996), it became apparent that, in terms of the model's potential value for improving understanding of long-term dynamics, two elements were central:

1. an ability to analyze the extent to which observed changes in overweight and obesity reflect the carrying over of BMI status from one stage of life to the next; and
2. an ability to evaluate outcomes over time for the entire population, with its changing age distribution, and not only for a single cohort or portion of the population.

Figures 3 and 4 summarize the model's current scope and structure. The right-hand side of Figure 3 depicts the population stock-flow structure, broken out by annual age (0-99) and sex and by four categories of body mass index (BMI). Our study does not address the issue of underweight: the "Not overweight" stock includes both underweight and normal-weight individuals. The definitions of the four BMI categories were developed specifically for the purposes of this modeling project in order to create mutually consistent and exhaustive population categories; they differ somewhat for infants, youth, and adults, as follows:

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- For infants (ages 0-23 months), the definitions are based on a comparison of weight-for-recumbent length (WRL) to recently revised growth chart percentiles (CDC/NHANES 2006). Not overweight: WRL<85th percentile; Moderately overweight: WRL≥85th percentile and <95th percentile; Moderately obese: WRL≥95th percentile and <99th percentile; Severely obese: WRL≥99th percentile.
- For youth (ages 2-19), the definitions are based on a comparison of BMI to standard growth chart percentiles, as well as a comparison to absolute BMI values. This dual test allows for a smooth transition in BMI definitions from youth age 19 to adults age 20. Not overweight: BMI<{85th percentile or 25}; Moderately overweight: BMI≥{85th percentile and 25} and <{95th percentile or 30}; Moderately obese: BMI≥{95th percentile and 30} and <{99th percentile or 35}; Severely obese: BMI≥{99th percentile and 35}.
- For adults (ages 20+), the definitions are based on absolute BMI values. Not overweight: BMI< 25; Moderately overweight: BMI≥25 and <30; Moderately obese: BMI≥30 and <35; Severely obese: BMI≥35.

The model aggregates across these BMI categories to determine the prevalences of overweight (=moderately overweight + moderately obese + severely obese) and obese (=moderately obese + severely obese). The model aggregates across ages to report prevalences for 10 age ranges, corresponding to age ranges for which we have prevalence data from NHANES: Ages 0-1, 2-5, 6-11, 12-19, 20-34, 35-44, 45-54, 55-64, 65-74, and 75+. In addition, the model aggregates across the entire 20-74 "adult" category, as defined consistently by all four NHANES surveys. The population structure also includes births, net immigration into the population, and deaths out of the population. The death rates differ according to age, sex, and BMI category. This portion of the model was supported by data (see Table 2) from the U.S. Census and Vital Statistics, as well as estimates of the impact of BMI category on death rates by age (Flegal et al. 2005).

Figure 4 shows in greater detail how the flows up and down the BMI chain are modeled in conjunction with annual aging of population cohorts. When passing from one age to the next, individuals may remain at the same BMI category, increase in BMI category ("up-flow"), or decline in BMI category ("down-flow"). As suggested in the left-hand side of Figure 3, the rates of up-flow and down-flow are determined by caloric balance, and may vary by age range (the 10 described above) and sex. Changes in caloric balance—which may vary by age, sex, and BMI category—are modeled as being affected by two broad classes of drivers that may relate to societal trends or planned interventions:

1. Changes in food or activity environments for entire segments of the population; and
2. Changes in the utilization or effectiveness of weight-control services for individuals.

A change in caloric balance is defined here to be the difference between changes in caloric intake and in caloric expenditure due to physical activity, not adjusting for metabolic and other types of regulatory compensation that typically accompany such changes (Livingston and Kohlstadt 2005, Saltzman and Roberts 1995, Bouchard et al. 1990). Human physiology and behavior have evolved multiple compensatory mechanisms that reduce the impact on weight of changes in caloric intake and physical activity. Even in high-calorie, low-activity environments, the compensatory mechanisms are still at work, although these environments do clearly tip the

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balance in the direction of weight gain. We have not at present attempted to model these compensatory mechanisms explicitly, but instead assume a fixed rate of conversion from caloric balance to changes in weight that implicitly adjusts for such mechanisms (see below under *Calibration of Constants*).

In the model, all caloric changes—including the impacts of societal trends or interventions—are expressed only in terms of their presumed net effects on caloric balance, not in terms of changes in caloric intake or changes in caloric expenditure per se. We have taken this approach because of a general lack of information on caloric expenditure and potentially unreliable or incomplete longitudinal data on caloric intake for individuals of different ages, sexes, and BMI categories.

Empirical Foundations and Data Limitations

The primary data source for understanding issues related to weight and BMI has been the four NHANES surveys, which allow one to trace the growth of overweight and obesity by sex for all ages through age 74 for the 1971-2002 period. (The three NHES surveys in the 1960s covered different age ranges at different times; see Table 1. Data on ages 75+ are available starting with the third NHANES survey 1988-1994.) The third and fourth NHANES surveys also oversampled smaller subpopulations in such a way as to provide reliable estimates by race and ethnicity, allowing one to see, for example, much higher rates of obesity in black and Mexican-American women than in their white counterparts. However, such decomposition of the population by race and ethnicity cannot be done reliably with the first two NHANES surveys, which did not oversample blacks and Mexicans-Americans as the later surveys did. Because we lack these data, we do not know to what extent the current prevalence disparities between whites, blacks, and Mexican-Americans existed back in 1971 and to what extent they emerged along with the growth in obesity overall. Consequently, we cannot evaluate the question of whether broad-based population policies could by themselves largely reverse the current racial/ethnic disparities, or whether focusing on black and Mexican-American groups separately is necessary to close significant gaps in overweight that may have existed even in the 1970s. Therefore, our current model is not broken out by race/ethnicity.

Another important data limitation has been the previously mentioned lack of reliable longitudinal data on caloric expenditure and caloric intake. Because of this limitation, it is not possible to analyze historically the impacts on caloric intake and expenditure from such factors as food price, smoking, sleeping time, television time, restaurant visit frequency, driving miles, physical education class frequency, and parental influence. Although time trend data exist on some of these factors individually, and some empirical or observational evidence suggest that they can impact calories, it is not possible to infer their respective magnitudes of influence on caloric intake and expenditure. If their magnitudes of influence are not known, one cannot reliably analyze the potential impacts of trends or interventions that would affect one or more of these factors. Therefore, our model does not include a breakout of the various individual factors affecting caloric intake and expenditure.

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Calibration of Constants

The formulation of the flow rates is central to the model's ability to accurately carry forward the consequences of changes in caloric balance. Each flow rate is the sum of a starting value for 1970 plus any change in the flow rate since 1970 due to a specified change in caloric balance. Consider first the starting values. The 1970s were, for the most part, a period of little or no growth in overweight and obesity, and make a convenient baseline for setting the flow rates. For each age range and sex, down-flow rates were set based on recent self-report data from NHANES (for adults) and from a comprehensive assessment of one-year BMI changes in school-age youth in the state of Arkansas. These data sources, along with all others used for model calibration, are listed in Table 2. Although these data sources are both from recent periods, we assume that the main determinants of weight loss—intentional dieting (*by BMI category*), illness, and natural age-related weight reduction among the elderly—are not significantly different in magnitude now than they were in 1970.

Having set the down-flow rates, the starting up-flow rates were then calibrated via an iterative process of simulation and adjustment. In particular, the up-flow constants were adjusted so that the model would remain in a near steady-state replicating the NHANES 1971-74 BMI prevalence data by age range and sex. For example, we infer from the NHANES data that the early-1970s prevalence of overweight for males had the following profile: around 15% for most of childhood; increasing steeply to around 60% by age 30; remaining at that level through age 55; declining gradually to about 50% by age 75; then declining more quickly in older age, for example to about 30% by age 90. The early-1970s prevalence of overweight for females appears to have a somewhat different profile: around 15% for childhood through age 15; rising gradually to about 50% by age 45; continuing to rise but more gradually to 60% by age 65; then declining gradually in older age, for example, to about 45% by age 90. Similar patterns of rise, plateau, and decline in the prevalence of excess weight over the life-course are observed in the NHANES 1971-74 data for the obese and severely obese. The model's up-flow constants were adjusted so that all of these patterns seen in the data are replicated.

Consider next the change in flow rates due to changes in caloric balance since 1970. To translate changes in caloric balance (relative to 1970) into changes in flow rates, one must first make assumptions about whether it is up-flows or down-flows that are affected. In particular, we assume that to the extent the changes in caloric balance are due to population-level environmental changes, and (a) represent a net increase, it is the up-flows that are affected, or (b) represent a net decrease, it is the down-flows that are affected. This formulation, while doubtless a simplification, is robust to large changes in caloric balance and allows for straightforward interpretation.

Changes in caloric balance due to new or extended weight control programs may (a) enhance weight loss and thus increase down-flows, and/or (b) prevent weight gain and thus reduce up-flows; a fraction is used to specify the extent to which such programs do (a) as opposed to (b).

Having established *which* flow rates will be affected, the model must also determine the magnitude of impact corresponding to a given change in caloric balance in order to explore intervention scenarios of varying strength and their consequences over the life-course. The

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parameters required for translating a change in caloric balance into a change in a flow rate are indicated in Table 2, and include (for each age range and sex) the cut-points for BMI categories (b_c), the median BMI within each BMI category (b_m), the median height (h_m), and an assumption for the average number of kilocalories per kilogram of weight change (k). For a given change in caloric balance (ΔK, expressed in kcal. per day), the equation used to approximate the consequent change in a flow rate (ΔF, expressed as a fraction per year) is as follows:

$$\Delta F = \text{MAX}\{0, 0.5 \times \Delta K \div [(b_c - b_m) \times (h_m)^2 \times k \div 365]\}$$

For the parameter k we use Forbes' (1986) empirical estimate of 8,050 kcal./kg., which is based on several studies of deliberate overfeeding in adults and implicitly takes into account the efficiency of weight deposition reflecting metabolic and other regulatory adjustments. This is an average that glosses over known differences among individuals, including differences by starting weight, by composition of the diet, and by the efficiency of weight deposition (Forbes 1986, Forbes 1987).

For simplicity, and to minimize the amount of speculation necessary about future changes, the median height (h_m) and median BMI (b_m) parameters are assumed to be constant over time. In regard to median height, the increase from 1971 to 2002 for any sex and age subgroup of adults does not exceed 1.5% (Ogden et al. 2004). In regard to median BMI within each BMI category (estimates extracted from NHANES for our modeling project), the data indicate for many of the sex and age subgroups some small movement upward over time, but by no more than 5% over the 30-year period.

To see how the above equation operates, consider an example: the up-flow rate to moderately obese for moderately overweight females age 55-64. Based on the calibration process described earlier in this section, we have estimated the 1970 value for this particular up-flow rate at 9.9% per year. For this population subgroup and up-flow, h_m=1.64 meters, b_m=27.0 kg./m^2, and b_c=30 kg./m^2. Now suppose that ΔK, the caloric imbalance relative to 1970, rises to +10 kcal./day. According to the equation, the impact on the up-flow rate, ΔF, is calculated as 2.8%. The implication is that an increase of +10 kcal/day would result in an increase in the up-flow rate from 9.9%/yr. to 12.7%/yr. (=9.9% + 2.8%).

Reproducing Past Growth and Estimating Past Changes in Caloric Balance

After constants were adjusted so that the model could reproduce the no-growth period of the 1970s, the next step in model calibration was to estimate increases in caloric balance capable of reproducing the NHANES-reported growth in overweight and obesity from the late 1970s through 2002. We assume that such increases in caloric balance were driven largely by "obesogenic" population-level changes in food and activity environments.

The utilization and effectiveness of weight-control services are assumed not to have decreased during the historical period. The inclusion of such services as an input to the model is intended for testing the impact of future interventions—that is, new or improved programs—that would cause some reduction in caloric balance, perhaps targeted by age, sex, or BMI category. One could, for example, simulate a new weight-control program that might—say, for reasons of

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maximizing cost-effectiveness—be targeted at only the severely obese but not other BMI categories.

The inferred changes in caloric balance due to environmental trends and interventions are specified with 60 time series. In particular, for each of the 20 combinations of age range and sex, a time series of changes in caloric balance—with zero representing caloric balance in 1970—is specified for the BMI categories of not overweight, moderately overweight, and obese. (Moderately obese and severely obese are assumed, for simplicity, to have the same changes in caloric balance.). Each time series specifies a value of zero in 1970, and then values at five year intervals after 1970 (1975, 1980, etc.); the model interpolates linearly between these specified values. To illustrate, Table 3 presents 12 of the 60 time series, specifically those for females in the 6-11, 12-19, 20-34, and 55-64 age groups.

The time series inputs for environmental influence were adjusted to reproduce the pattern of growth of overweight, obese, and severely obese prevalences reported by NHANES for each age range and sex. Because the prevalences in younger ages carry over to older ages (as suggested by Figure 4), the strategy for such calibration was to proceed from youngest to oldest. Also, within each age category, we found it advantageous in general to calibrate first overweight, then obese, and then severely obese. We also made the following assumptions during calibration:

1. that inputs for environmental influence were greater than or equal to zero for all ages throughout the historical period. It seems unlikely that some age ranges would have negative caloric balances relative to 1970 in the context of an environment that has become obesogenic for all ages.

2. that the inputs for 2005 were identical to those for 2000. This follows the observation from calibration that in most cases the estimated inputs for 2000 were identical or very close to those for 1995, suggesting that the caloric imbalances had for the most part stabilized by 2000.

An example of the model's ability to reproduce history—for one of the 20 age range and sex combinations—is presented in Figure 5. This example focuses on females age 55-64, and presents graphs for overweight, obese, and severely obese fractions as reported by NHANES (wide vertical bars) and as simulated (continuous line). The wide vertical bars for the NHANES data reflect the fact that each survey spanned multiple years. The "base run" simulation results seen in Figure 5 reflect two factors leading to prevalence growth: (1) the carryover of increasing BMI status from younger age categories, and (2) some additional growth due to positive caloric balance for the 55-64 age category in question. The estimated caloric balances relative to 1970 for females age 55-64 (see Table 3) are rather small, staying at zero through 1980, growing to less than +20 kcal. per day by 1990 (varying some by BMI category), and actually declining to no more than +10 kcal. per day by 1995 and beyond. Changes of this magnitude may be significant, even though they are unlikely to be detected through public health surveillance.

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This example illustrates some general findings from the calibration process, as follows:

1. The best simulated fit to the data is in most cases obtained with inputs leading to curves that grow in S-shaped fashion, with acceleration in the 1980s turning to linear growth in the early 1990s, then turning to marked deceleration in the mid-to-late 1990s. This result is seen for all prevalence graphs except for those of the 6-11 age group (both male and female), which exhibit more prolonged linear growth through 2005 before flattening.

2. The increasing prevalence in younger age groups contributes significantly to growth in successively older age groups. This becomes evident in the calibration process, which at each age starts with the caloric balances relative to 1970 set to zero before they are adjusted upward. In some cases, the carryover from one age group explains a large portion of the growth seen in the next older age group. This is true, for example, in the case of males age 12-19, where nearly all of the historical growth (from 1976 to 2002; see Table 1) appears to be a carryover from the age 6-11 group, and where the estimated caloric balances relative to 1970 are consequently never more than +5 kcal. per day.

3. The estimated caloric imbalances relative to 1970 never exceed +25 kcal. per day for children and adolescents, and never exceed +45 kcal. per day for any of the adult age ranges, regardless of BMI category. For a woman initially consuming, say, 1600 kcal. per day, +45 kcal. represents only a 2.8% increase. For a man initially consuming, say, 2500 kcal. per day, +45 kcal. represents only a 1.8% increase.

4. Nearly all of the estimated caloric balance curves for 1970-2000 follow either a pattern of monotonic growth up to a peak, or a pattern of growth followed by some decline; examples of both patterns may be seen in Table 3. The timing of the growth and (if applicable) decline in caloric balance varies from subgroup (age, sex, BMI category) to subgroup. For most subgroups, the estimated growth in caloric balance begins in the late 1970s or early 1980s, and reaches its peak by 1990 or 1995.

5. The largest estimated caloric imbalances for a given sex and age group are not necessarily found among the obese, as one might guess, but (as Table 3 illustrates) are often among the moderately overweight or the not overweight. Note that the caloric imbalances for a particular BMI category are considered relative to the 1970 baseline for that BMI category. Thus, the caloric imbalance for the obese, *relative to the baseline for the obese*, may be less than the caloric imbalance is for lower BMI categories, relative to their baselines.

Uncertainties in Model Calibration and Assumptions

The model's constants and time series inputs are all subject to some degrees of uncertainty. The impact of this uncertainty on the findings above may be evaluated through sensitivity analysis, which, for each round of analysis, requires recalibration of the model so that it again fits the historical prevalence data. Because we have not yet performed any systematic sensitivity analysis of the model, our confidence in the above findings thus must be characterized as incomplete. It may prove useful to perform sensitivity analyses in the following specific areas:

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1. Down-flow rates: The procedure for calibrating these parameters was informed by data sources that were the best available to us, but nevertheless limited. Information on annual adult weight change came from self-reported responses in NHANES, which may have been biased overall and perhaps differentially by BMI category. Information on youth BMI fluctuations used direct physical measures from Arkansas schoolchildren , but could not address possible differences between Arkansas and the rest of the country. What difference might it make to the above findings if these parameters were varied within their ranges of uncertainty?

2. Impact of environment on down-flow rates: Changes in caloric balance originating from shifting environmental conditions were assumed to affect only the up-flows and not the down-flows. What difference might it make if the model were modified to allow some fraction of the change in caloric balance to affect the down-flows and not only the up-flows?

3. Caloric balance time series: The estimated time series inputs (such as those in Table 3) display some irregularity or non-uniformity that may appear unrealistic in some ways. What difference might it make if these time series were constrained to look more as expected?

4. Uncertainty in prevalence data: The NHANES prevalence data themselves are estimates subject to sampling error. To what extent might some of the above findings, such as the 1990s deceleration in prevalence growth, be affected by this sampling error?

Exploring the Extent to which Caloric Imbalances and Weight Increases at Younger Ages Have Contributed to the Growth of Obesity at Older Ages

We noted previously in discussing model calibration that increasing weight in younger age groups appears to contribute significantly, over time, to increasing weight in successively older age groups. "What-if" simulations of the past can help to quantify that observation and shed light on its implications. In particular, we present three simulations in which for some younger age groups (and for both sexes and all BMI categories) the estimated increases in caloric balance relative to 1970 are set to zero, as if the changing food and activity environments had not affected those age groups, but only the older age groups.

Figure 6 presents, alongside the base run results, representative output from these alternative simulations of the past (1970-2005), showing for both males and females the obese fractions for two age groups: adolescents (age 12-19) and adults (age 20-74). The assumed conditions for the alternative simulations (and the shorthand simulation names used in Figure 6) are as follows:

- *Youth*: The caloric imbalance is eliminated for all youth ages 0 to 19;
- *Youth+YoungAdult*: The caloric imbalance is eliminated for all youth 0-19 as well as for all young adults age 20-44;
- *All*: The caloric imbalance is eliminated for all ages 0-99.

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The results are qualitatively identical for males and females. The impact on adolescent obesity (in Figures 6a and 6c) of zeroing out caloric imbalances for all youth (as is the case for all three of the alternative simulations) is, not surprisingly, to eliminate its growth entirely. Similarly, when the caloric imbalances for all ages are zeroed out , then the growth in the adult obese fractions (in Figures 6b and 6d) is entirely eliminated as well. But when the zeroing out of caloric imbalance is limited to youth, only a small fraction of the growth in overall adult obesity through 2005 is eliminated: this relative reduction is 6% for males and 10% for females (see Figures 6b and 6d). On the other hand, when the zeroing out of caloric imbalance includes both youth and younger adults, then a majority of the growth in adult obesity is eliminated: this relative reduction is 63% for both males and females.

The rather small impact of youth on adults seen in Figure 6 may seem surprising, particularly in light of our previous comment that younger ages have significant impact on successively older ages. A more detailed look at the simulation results reveals that the impact of youth on the youngest category of adults in the model, age 20-34, *is*, in fact significant: the reduction of obesity in the 20-34 age group in the *Youth* simulation is 25% for males and 29% for females. However, the impact of youth on adults age 20-34 becomes largely diluted when considering all adults age 20-74. This is so for two reasons: first, the 20-34 age group accounts for only about 20% of adults age 20-74; and second, the adults themselves have significant caloric imbalances that drive their prevalence of obesity upward in the base run. These adult imbalances cause further increases in obesity much beyond those attributable to carryover from youth.

The relatively large combined impact of youth and young adults on all adults age 20-74 is also notable. Young adults 20-44, whose caloric imbalances are zeroed out in the *Youth+Young Adult* simulation, amounted to slightly over 50% of the entire adult 20-74 population in 2005. The 63% reduction in obesity growth for all adults in this simulation suggests that the elimination of overweight and obesity growth in younger adults has a significant carryover effect for older adults.

Exploring the Extent and the Time Frame over which Age-Based Interventions Could Plausibly Reverse the Growth of Obesity in the Future

Having used the model to gain a better understanding of the past, we can now use it to identify and investigate plausible futures. Our hypothetical base case is one in which the estimated caloric imbalances remain unchanged at their 2000 values through to the end of the simulation in the year 2050. Figure 7 presents obesity fractions for adolescents and adults, broken out by sex, for the entire simulated period 1970 to 2050. The base case result is the uppermost line in each of the four graphs. For adolescents, the obese fractions continue to rise a little more past their 2005 values but are flat by 2015. The obese fraction for male adolescents increases from about 18% in 2005 to a final value of 21%; for female adolescents, the increase is from 17% to 19%. For adults, however, the obese fractions continue to climb right through 2050, though the amount of increase after 2030 is small. The obese fraction for male adults increases from 30% in 2005 to 34% by 2050; for female adults, the increase is from 37% in 2005 to 44% by 2050.

The future base case illustrates the prolonged consequences of the carryover effect for the adult population. Thirty or more years pass from the time that the caloric balances at all age levels are

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assumed to stop changing to the time that the carryover effect, from youth to younger adults to older adults, no longer causes significant further increases in obesity for adults.

Alongside the base case, Figure 7 presents results for three alternative futures intended to represent interventions that might be developed to reverse the growth in obesity through changes in food and activity environments. We imagine that these interventions are aimed initially at school-age youth—perhaps using the schools as their focus—but that by linking these interventions to wider social networks they may also expand to also reach the parents of these youth, or even the entire community. The interventions are assumed to be quite effective at changing the behavior of their beneficiaries, in each case eliminating the caloric imbalances that have emerged since 1970. Even though such interventions are not presently well characterized, it is instructive to study their potential consequences. In each of these alternative scenarios, the intervention starts to be implemented in 2005, but does not come to full fruition, in terms of its behavioral effects, until 2015; that is, we assume a 10-year ramp-up period.

The three intervention scenarios (and the shorthand simulation names used in Figure 7) are as follows:

- *School Youth*: The intervention is assumed to impact all youth ages 6-19, but does not impact caloric imbalances for other age ranges;
- *School Youth+Parents*: The intervention is assumed to impact both school-age children and their parents. Using year 2000 data on birth rate by age of mother (CDC/NVSS 2006), we have developed estimates of the fraction of women in each of the model's adult age ranges with at least one child age 6-19. These estimates are as follows: age 20-34: 35%; age 35-44: 75%; age 45-54: 40%; age 55-64: 5%. We assume that the fraction of men in each age range who are fathers of school-age youth is the same as these fractions for women. To represent the impact of the intervention for a given adult age range, the caloric imbalance relative to 1970 is eliminated only by the fraction of the age range estimated to be parents of school-age youth. This reflects a weighted average of a reduction to zero for the parents, and no reduction for the non-parents.
- *All*: The intervention is assumed to impact all people of all ages: all caloric imbalances relative to 1970 are reduced to zero by 2015. This includes all those missed in the previous scenario, namely pre-school children and adults other than parents of school-age children.

The results are qualitatively similar for males and females. It is useful to start by examining the results of *All*, the scenario with comprehensive community-wide impact, and then to gauge the impacts of the less comprehensive scenarios relative to those of *All*. For adolescents, the reduction of all caloric balances back to their 1970 values causes the obese fractions to return to their 1970 values by around 2025; that is, just 10 years after the intervention has become fully effective. For adults age 20-74, though, the reduction of the obese fractions to their 1970 values does not occur until at least 2040, and in the case of females is still not back to its 1970 value by the simulation's end in 2050. In the same way that the growth of obesity takes a few decades to develop and carry over fully through the adult population, the reduction of obesity to its 1970 levels (based on a reduction of caloric imbalances to their 1970 values) will also require a few decades to play out fully.

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As a corollary, adult obesity prevalences could decline to their 1970 levels more quickly only if interventions reduced caloric balances, at least temporarily, to something *less than* their 1970 values. In simulations not reported here, we have experimented with scenarios that combine the population-level programs reflected in Figure 7 with an individual-level weight-loss program for the obese and severely obese for a period of 10 years. In general, those experiments suggest that if the weight-loss program is sufficiently broad in its coverage and effective, this combined intervention could reduce obesity to its 1970 level before the 10 years of the weight-loss program are complete, a level that can thereafter be maintained by the population-level environmental changes. A powerful though temporary weight-loss program can, in effect, reconfigure the population age-and-weight structure so that the population-level programs do not have to contend with decades of further carryover effects.

Let us now consider the impacts of the less-comprehensive population-level intervention scenarios, *School Youth* and *School Youth+Parents* relative to those of *All*. With respect to adolescents, the difference between the comprehensive and the less-comprehensive interventions is that the comprehensive intervention addresses not only school-age youth (6-19), but also children less than age 6. This difference is reflected in the gap between the lower line and the middle line in Figures 7a and 7c, which for both males and females amounts to about 30% of the final gap between the base case and *All*. In other words, the model suggests that a program that addresses school-age youth but does not address pre-school children would leave 30% of potential obesity reductions in adolescents unrealized or "on the table" due to carryover effects from pre-school age up through adolescence.

With respect to adults, the impact of an intervention that addresses only school-age youth is rather small. Specifically, the *School Youth* intervention has an impact on adult obesity relative to that of the comprehensive *All* intervention that is only 9% for males and about 11% for females. (This result may be compared to the 6% and 10% reductions discussed above in connection with Figure 6 and the *Youth* simulation.) The effect of overweight and obesity carryover from adolescence to adulthood is small relative to the cumulative effect of sustained caloric imbalances during adulthood.

The impact of an intervention that addresses school-age youth and their parents has a moderate-sized impact on the adult obese fractions, reducing those fractions by 2050 to where they were in the late 1990s. This reduction amounts (for both males and females) to 42% of the impact seen in the comprehensive *All*. (This result may be compared to the 63% reductions discussed above in connection with Figure 6 and the *Youth+Young Adults* simulation.) Because a disproportionate fraction of the excess weight accumulated during adulthood is put on during early and middle adulthood, programs that would reduce caloric imbalances among parents of school-age youth can help significantly in addressing adult obesity overall. However, as Figures 7b and 7d make clear, if one hopes to see significant *reductions* in adult obesity, and not just the prevention of further increases, then even the youth-and-parents intervention is not enough, and a more comprehensive approach is needed. Realistically, this may require transformations of food and activity choices within institutions beyond the school, such as worksites, faith-based institutions, restaurants, markets, parks, and more.

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Limitations

Dynamic models cannot render definitive answers to policy questions (Sterman 2002). Data limitations and other practical considerations (e.g., time, money, personnel available) mean that any model will be circumscribed in its breadth, depth, and degree of precision. The model described here should therefore be seen not as a tool for rendering final decisions, but rather as a tool to support the development of obesity prevention goals and policies.

We have already noted limitations related to the lack of data in some areas. Unreliable, incomplete, or insufficiently detailed longitudinal data on caloric intake and expenditure have led to a model that starts with assumptions about changes in caloric balance and does not reach further back to understand the relative contributions of various trends and interventions in affecting caloric balance. Similarly, a lack of sufficiently large sample sizes for blacks and Mexican-Americans in the first two NHANES surveys has led to a model that cannot speak to the potential effectiveness—in regard to both reducing disparities and reducing overall population obesity in the US—of programs tailored specifically to these subpopulations.

We have also noted limitations related to the uncertainty associated with some of the model's assumptions. These include: (a) the down-flow rate constants; (b) the assumption that all of the impact of environment-originated changes in caloric balance are on up-flow rates rather than down-flow rates; (c) the dozens of caloric balance time series inputs, which in some cases appear irregular or non-uniform; and (d) uncertainty in the NHANES prevalence data themselves. More extensive analyses are needed to determine how robust the model's results are to uncertainties in these assumptions.

The model is further limited due to its compartmental structure, treating populations in the aggregate rather than as individuals. Because the model does not trace individual life histories, it cannot, for example, show how obesity in childhood may lead to a greater likelihood of very severe and costly obesity as an adult (Serdula et al. 1993, Freedman et al. 2001, Must et al. 1992).

Finally, the causal theory underlying this model focuses only on the dynamic effects of caloric balance and the carryover of BMI status from one age to the next. It does not address how learned habits may persist or change from childhood, through adolescence, and into adulthood. Lacking information to the contrary, we have assumed that people's habits are determined by the choices available to them in their present circumstances, and that even those who had previously maintained caloric balance would eventually change their weight-related habits if consistently exposed to food and activity environments that do not support caloric balance.

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Conclusions

Although data limitations have dictated that the scope of the model be narrower than we might have wanted, the obesity dynamics model is nevertheless a valuable resource for studying the life-course dynamics of weight change and the potential consequences of various intervention strategies. While the real effects of interventions can only be discovered through implementation and evaluation, careful scenario planning and simulation modeling can increase the chances of developing an effective health protection strategy. As far as we know, no other analytical model has been developed to systematically play out the effects of changes in caloric balance on age- and sex-specific prevalences of overweight and obesity over the life-course for the U.S. population. With its ability to reveal plausible short- and long-term consequences of changes in caloric balance, our model could help planners and policy makers establish an explicit rationale for their goals and develop appropriate intervention strategies throughout the life-course. Specifically, the model is capable of

- showing how the carryover of BMI status from one year to the next affects overweight and obesity prevalence over the life-course; and
- tracing the plausible impacts over time of population-level interventions that (a) alter food and activity environments, or (b) bolster individual-level services for weight loss or weight maintenance.

At least four general conclusions may be drawn from the results of the simulation experiments reported here:

1. An inflection point in the growth of overweight and obesity prevalences probably occurred during the 1990s. Extrapolations assuming continued linear growth may therefore exaggerate future prevalences.

2. The daily caloric imbalance relative to 1970 that accounts for the growth of obesity is estimated to be in the range of 1-3% of daily caloric intake. This result is consistent with simple intuitive calculations. For example, for a person whose weight is stable at 2000 kcal. per day, a caloric excess of 2%, or 40 kcal. per day, will (assuming deposition of 8,050 kcal. per kg.) produce a weight gain of 1.8 kilograms in one year of a multi-year trajectory to obesity. It is also consistent with another analysis of NHANES data that estimated a median population excess of 15 kcal. per day could explain the historical increase in mean population BMI (Hill et al. 2003).

3. The current trend to focus intervention efforts on school-age children, if not effectively linked to the rest of the community, will have only a relatively small impact on the problem of obesity in the adult population. More comprehensive efforts at all ages are needed to avoid the high costs and heavy burden of disease due to adult obesity (Finkelstein and Wang 2004, Wang et al. 2003, Wang et al. 2002).

4. Even if we succeed as a society in creating conditions that support caloric balance by 2015, it will take decades more for the full effects of that work to become visible across the adult population. One avenue to accelerate progress may be to expand the availability

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of appropriate forms of individual weight control services. However, those services are fraught with their own costs and difficulties such as diet failure and recidivism.

The model does not indicate the exact nature of the interventions envisioned in the simulations presented here, nor are there well-defined best practices in the field. Also, issues of intervention effectiveness and cost are beyond the scope of the model. As a result, any policy-related conclusion presented here—such as the statement that a comprehensive, all-ages approach is needed in order to reduce adult obesity successfully—should be read as a logical inference from the model, not as a policy recommendation per se.

The scenarios explored here, along with others that could be simulated in the model, reveal a number of plausible trajectories into the future, including some that may be more desirable than others. The current model is a work in progress and leaves unaddressed questions about the exact nature of the programs and policies that are needed to effect change. Nevertheless, it can inform policy discussions concerning the consequences—for whom, by how much, and by when—of national efforts to reverse the growth of obesity.

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Table 1. Overweight, obese, and severely obese fractions for four age ranges, 1960-2002

	NHES			NHANES			
	1960-62	1963-65	1966-70	1971-74	1976-80	1988-94	1999-2002
MALE & FEMALE COMBINED							
Overweight							
Age 2-5				15.7%	14.2%	18.0%	22.4%
Age 6-11		13.0%		13.9%	15.5%	24.8%	31.2%
Age 12-19			14.3%	16.5%	14.3%	24.5%	30.9%
Age 20-74	44.9%			47.3%	47.1%	55.9%	65.2%
Obese							
Age 2-5				4.8%	5.0%	7.2%	10.3%
Age 6-11		4.2%		4.0%	6.5%	11.3%	15.7%
Age 12-19			4.6%	6.1%	5.1%	10.5%	16.1%
Age 20-74	13.4%			14.6%	15.0%	23.3%	31.1%
Severely obese							
Age 2-5				1.5%	1.1%	2.5%	3.6%
Age 6-11				0.4%	1.2%	2.7%	3.8%
Age 12-19				0.7%	0.5%	1.7%	3.2%
Age 20-74				4.2%	4.6%	8.4%	13.0%
MALE							
Overweight							
Age 2-5				17.1%	12.8%	16.9%	22.9%
Age 6-11				14.9%	16.4%	25.3%	32.4%
Age 12-19				15.6%	14.4%	24.0%	31.2%
Age 20-74	49.0%			53.8%	52.6%	60.9%	68.7%
Obese							
Age 2-5				4.9%	4.6%	6.2%	10.0%
Age 6-11				4.3%	6.7%	11.6%	16.6%
Age 12-19				6.0%	4.8%	11.3%	16.7%
Age 20-74	10.7%			12.1%	12.7%	20.6%	28.1%
Severely obese							
Age 2-5				1.7%	1.7%	2.3%	3.4%
Age 6-11				0.6%	1.2%	2.7%	4.8%
Age 12-19				0.9%	0.6%	2.2%	4.5%
Age 20-74				2.3%	2.4%	5.5%	9.7%
FEMALE							
Overweight							
Age 2-5				14.2%	15.7%	19.2%	22.0%
Age 6-11				12.9%	14.6%	24.2%	29.9%
Age 12-19				17.4%	14.2%	25.0%	30.5%
Age 20-74	40.2%			40.9%	42.0%	51.0%	61.7%
Obese							
Age 2-5				4.8%	5.4%	8.2%	10.6%
Age 6-11				3.6%	6.4%	11.0%	14.7%
Age 12-19				6.2%	5.3%	9.7%	15.4%
Age 20-74	15.7%			16.6%	17.1%	25.9%	34.0%
Severely obese							
Age 2-5				1.3%	0.5%	2.7%	3.8%
Age 6-11				0.2%	1.3%	2.7%	2.6%
Age 12-19				0.5%	0.4%	1.1%	1.8%
Age 20-74				5.9%	6.6%	11.1%	16.2%

Numbers in red may be unreliable due to small sample sizes or large standard errors.

Definitions for Ages 2-19 (NHES): Overweight BMI>=85th percentile, Obese BMI>=95th percentile on CDC growth chart.

Definitions for Ages 2-19 (NHANES): Overweight BMI>=25 or 85th percentile, Obese BMI>=30 or 95th percentile, Severely obese BMI>=35 or 99th percentile on CDC growth chart.

Definitions for Ages 20-74: Overweight BMI>=25; Obese BMI>=30; Severely obese BMI>=35

Information on NHES and NHANES may be found at http://www.cdc.gov/nchs/nhanes.htm.

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Table 2. Sources of data used in the model

Topic Area	Data Source
Prevalence of Overweight and Obesity	
Body mass index (BMI) category prevalence by sex and age (10 age ranges)	National Health and Nutrition Examination Survey (1971-2002)
Translating Caloric Balances into BMI Flow-Rates	
BMI category cut-points for children and adolescents	CDC Growth Charts (Revised 2000; see CDC/NHANES 2006)
Median BMI within each BMI category	National Health and Nutrition Examination Survey (1971-2002)
Median height	
Average number of kilocalories per kilogram of weight change	Forbes 1986
Estimating BMI Category Down-Flow Rates	
In adults: Self-reported 1-year weight change by sex and age	National Health and Nutrition Examination Survey (2002)
In children: BMI category changes by grade and starting BMI category	Arkansas statewide pre-K through 12th grade assessment (2004-2005)
Population Composition	
Population by sex and age	U.S. Census and Vital Statistics (1970-2000 and projected)
Death rates by sex and age	
Birth and immigration rates	
Influence of BMI on Mortality	
Impact of BMI category on death rates by age	Flegal, Graubard, et al. 2005.

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Table 3. Estimated caloric imbalances (kilocalories per day) relative to 1970 for females in four selected age ranges, 1970-2005

	ESTIMATED CALORIC IMBALANCES RELATIVE TO 1970							
FEMALE	1970	1975	1980	1985	1990	1995	2000	2005
Age 6-11								
Not overweight	0	0	2	2	7	8	10	10
Moderately overweight	0	6	19	19	14	12	12	12
Obese	0	0	6	6	4	3	3	3
Age 12-19								
Not overweight	0	0	0	5	12	15	17	17
Moderately overweight	0	0	0	0	0	10	19	19
Obese	0	0	0	0	0	4	6	6
Age 20-34								
Not overweight	0	0	0	5	17	29	41	41
Moderately overweight	0	0	0	27	39	37	37	37
Obese	0	0	0	6	19	15	15	15
Age 55-64								
Not overweight	0	0	0	8	18	10	10	10
Moderately overweight	0	0	0	2	6	0	0	0
Obese	0	0	0	9	11	6	6	6

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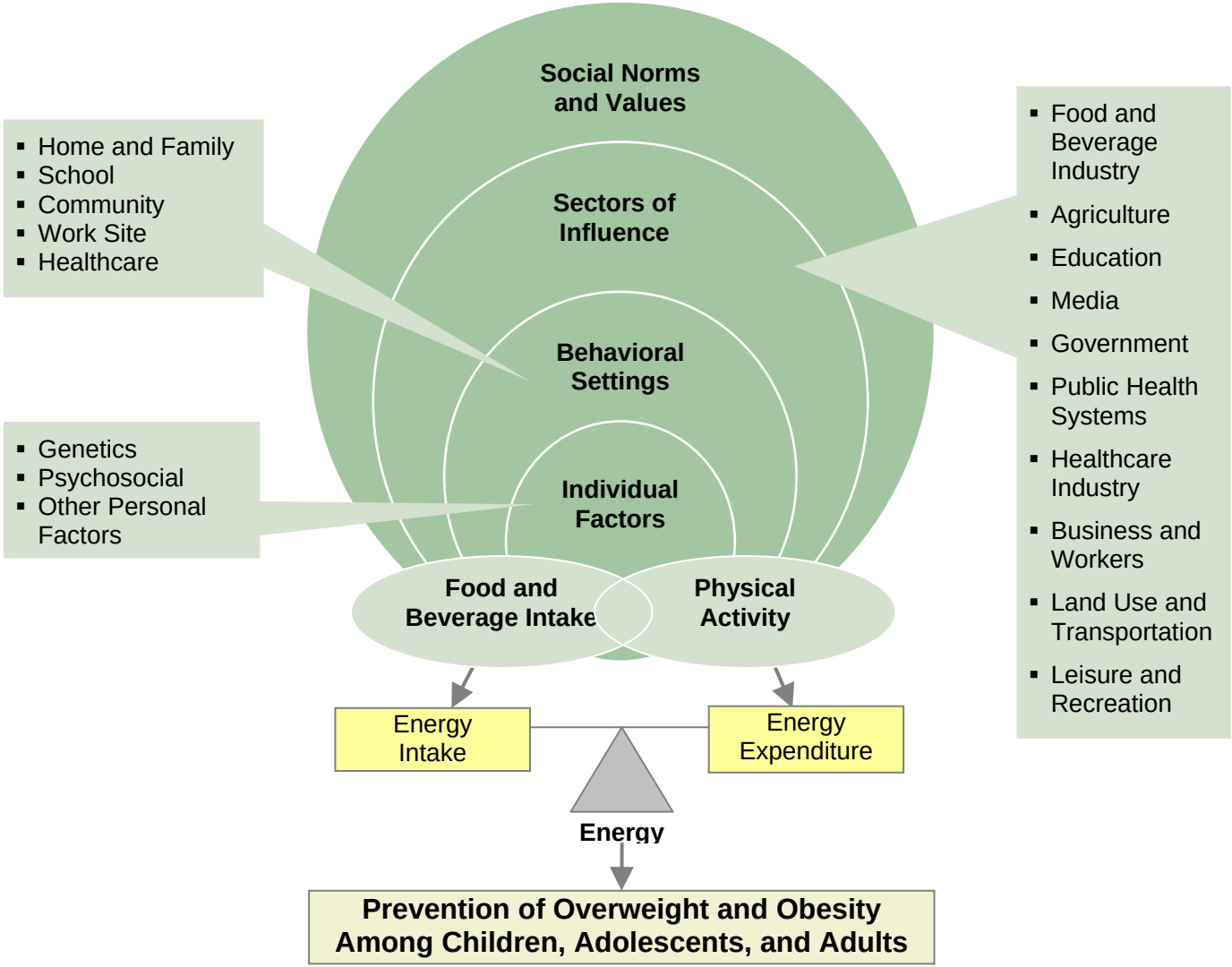
Figure 1. An ecological framework for organizing influences on overweight and obesity



Note: Adapted from IOM 2005 (Figure 3-2, p.85)

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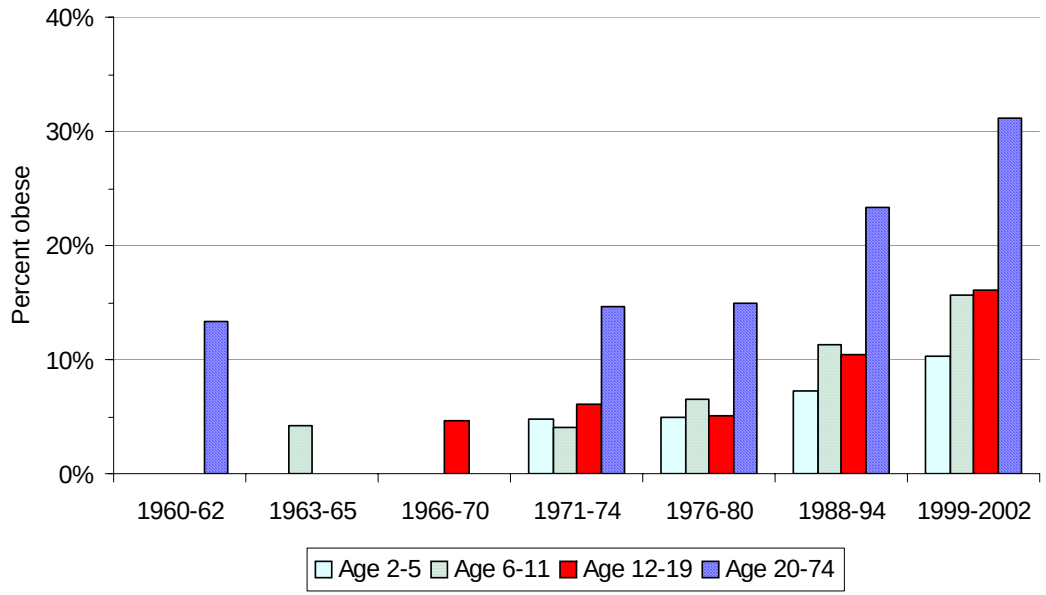
Figure 2. Growth of obesity prevalence for four age ranges, 1960-2002 (sources: NHES, NHANES)



Definitions of obese for this study:

Ages 2-19, 1960-1970 (NHES):	BMI$\geq$95th percentile on CDC growth chart;
Ages 2-19, 1971-2002 (NHANES):	BMI$\geq$30 or BMI$\geq$95th percentile on CDC growth chart;
Ages 20-74 (NHES, NHANES):	BMI$\geq$30.

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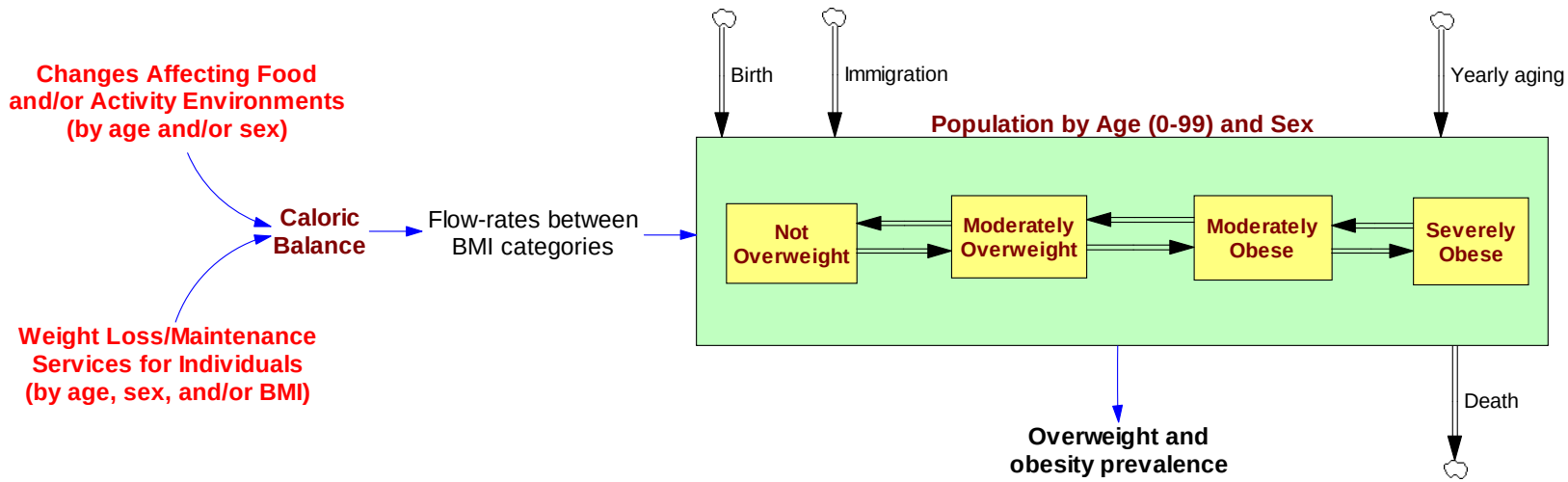
Figure 3. Overview of model structure



Category Definitions

- For infants (ages 0-23 months): Not overweight: weight-for-recumbent length (WRL)<85th percentile; Moderately overweight: WRL≥85th percentile and <95th percentile; Moderately obese: WRL≥95th percentile and <99th percentile; Severely obese: WRL≥99th percentile.
- For youth (ages 2-19): Not overweight: BMI<{85th percentile or 25}; Moderately overweight: BMI≥{85th percentile and 25} and <{95th percentile or 30}; Moderately obese: BMI≥{95th percentile and 30} and <{99th percentile or 35}; Severely obese: BMI≥{99th percentile and 35}.
- For adults (ages 20+): Not overweight: BMI< 25; Moderately overweight: BMI≥25 and <30; Moderately obese: BMI≥30 and <35; Severely obese: BMI≥35.

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Figure 4. Body mass index (BMI) category transitions over the life-course

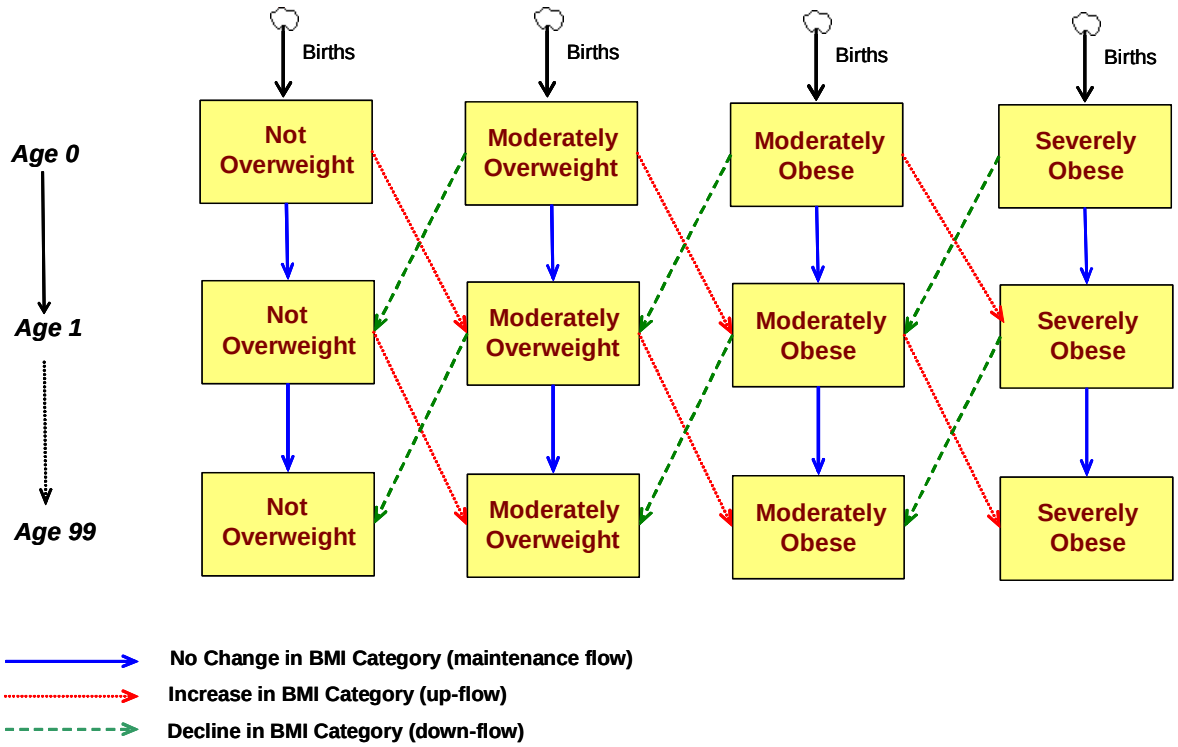

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Figure 5. Base run comparisons to historical data for one of 20 {sex, age} subgroups: Females age 55-64

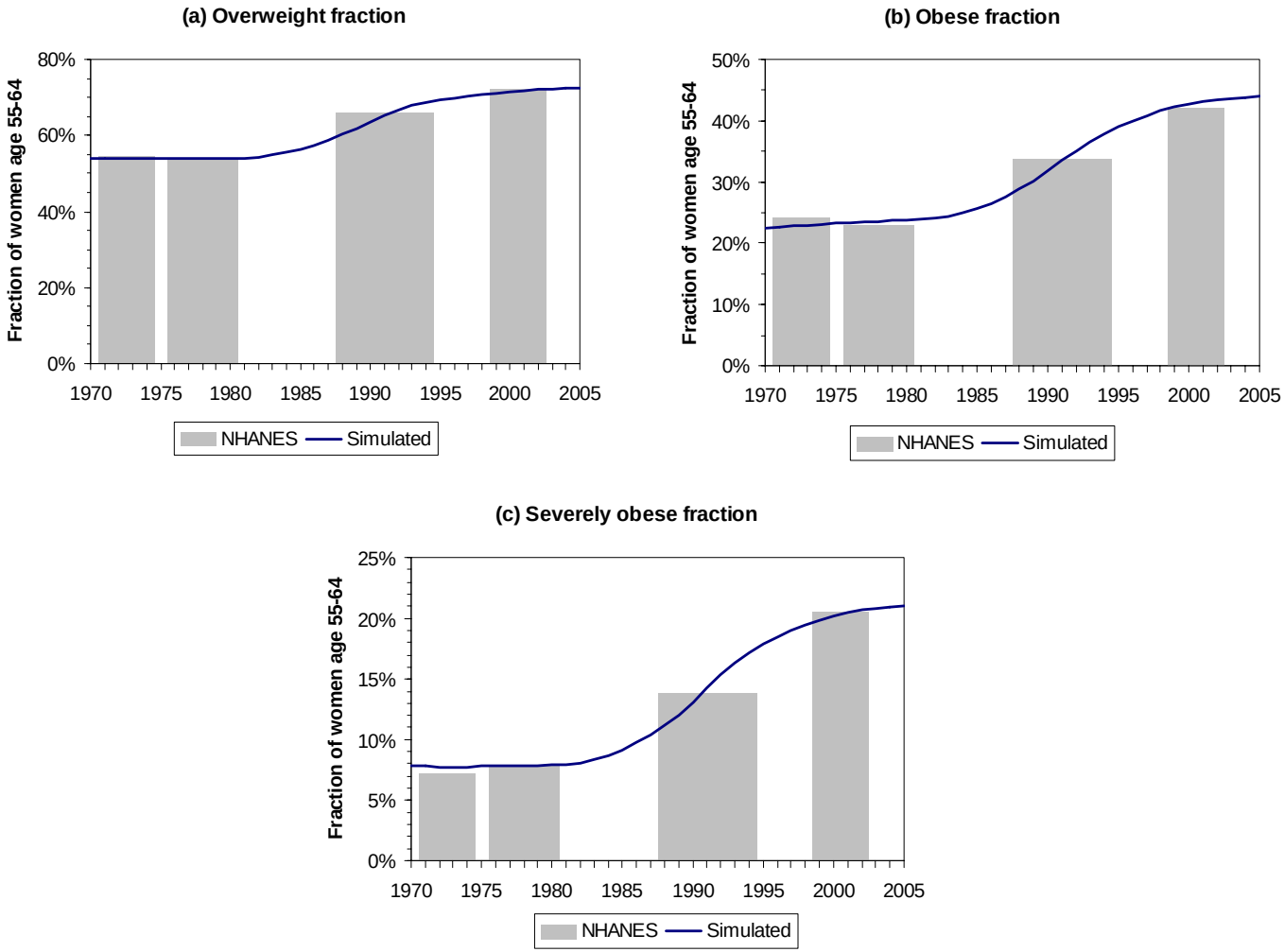

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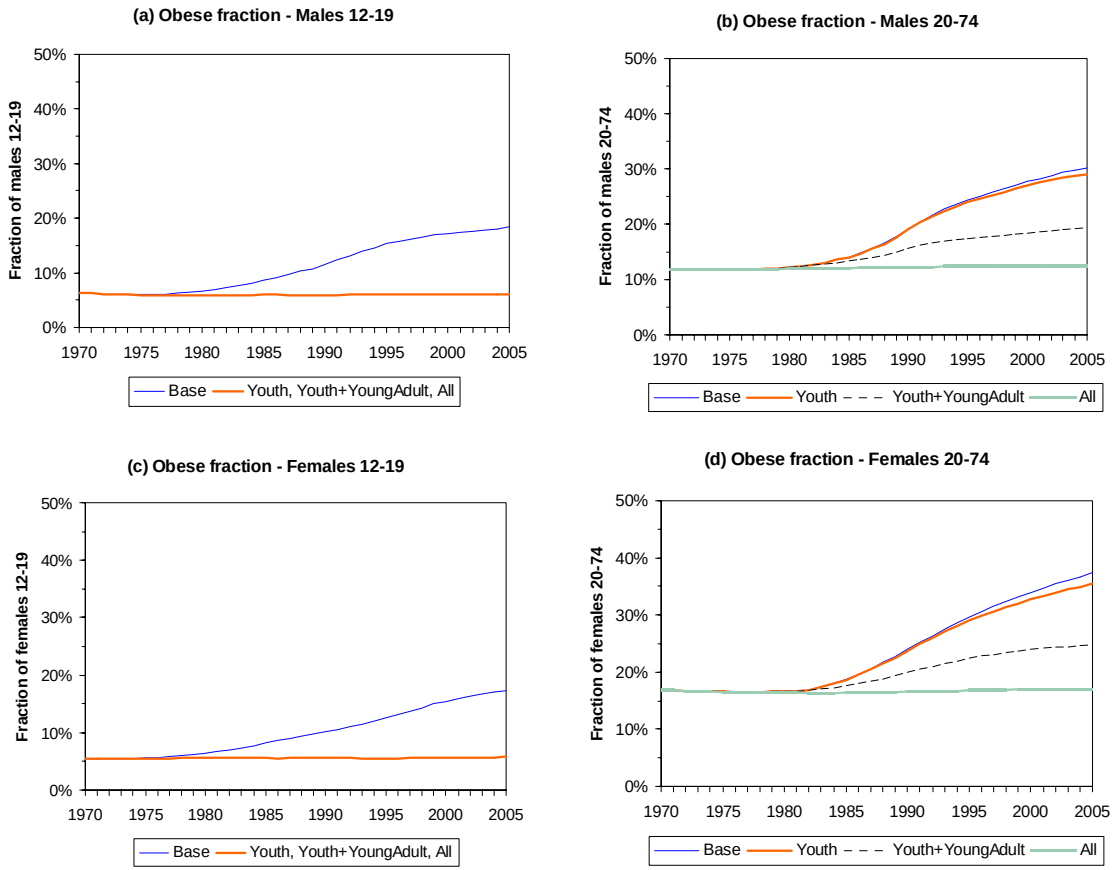
Figure 6. Obese fractions of adolescents and adults by sex, under base run and three alternative pasts, 1970-2005



Note: In each of the three alternative pasts, it is assumed that, for a specified age range, caloric balance does not increase from 1970 onward. In "Youth", that age range is 0-19; in "Youth+YoungAdult" it is 0-44; in "All" it is all ages (0-99).

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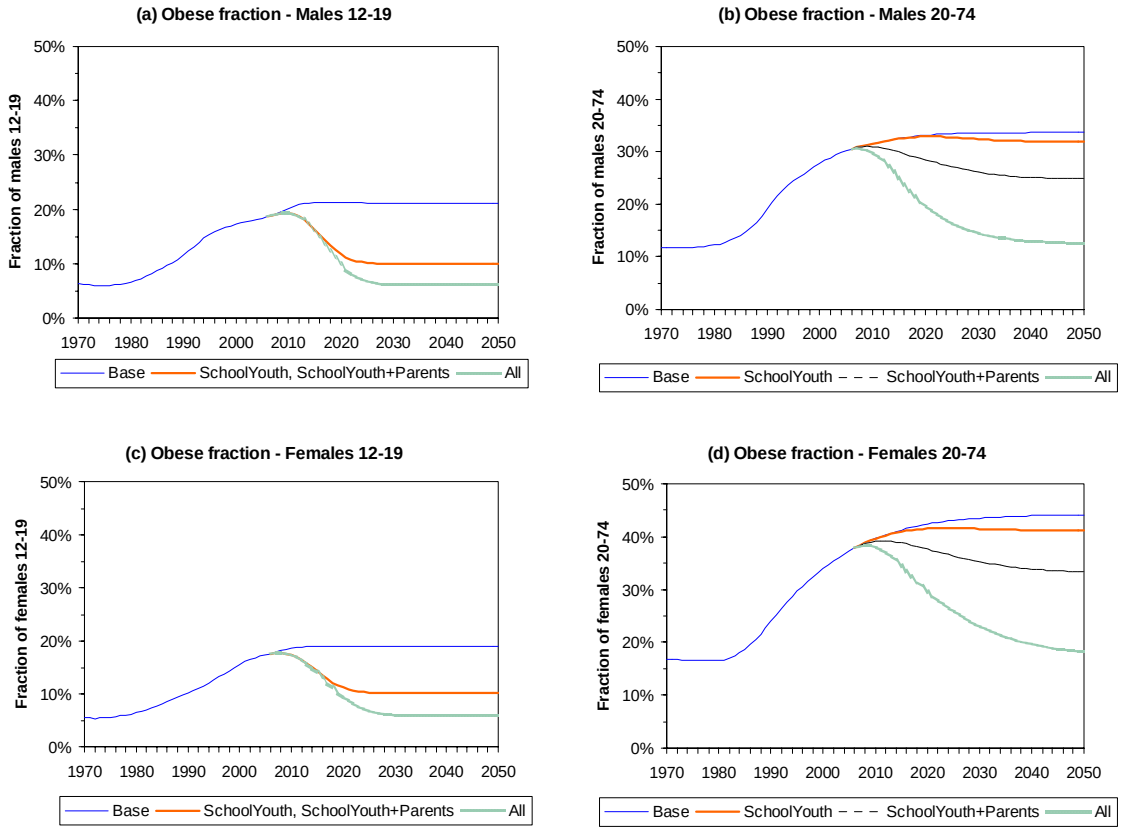
Figure 7. Obese fractions of adolescents and adults by sex, under base run and three alternative futures, 1970-2050.



Note: In each of the three alternative futures, it is assumed that, for specified age ranges, caloric balance ramps down during 2005-2015 back to its 1970 value. In "SchoolYouth", that age range is 6-19; in "SchoolYouth + Parents", the age range is school-age youth plus their parents—35% of age 20-34, 75% of age 35-44, 40% of age 45-54, and 5% of age 55-64; in "All", the reduction applies to everyone of all ages.

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