Impacts of Salt Intake Reduction Interventions on Medical and Long-term Care Costs in Japan

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ABSTRACT
Excessive salt consumption is associated with an elevated risk of cardiovascular diseases (CVD) and chronic kidney disease (CKD) within the Japanese population. This study endeavors to examine the potential health and economic outcomes resulting from the diminution of salt intake via food reformulation and adopting a low-salt diet among the Japanese populace. A system dynamics model was developed to evaluate the impact of interventions designed to curtail salt consumption on the average dietary salt intake, the prevalence of salt-related illnesses, and their consequential costs at a national scale in Japan. The findings suggest that, all of the proposed interventions, including mandatory and voluntary food reformulation, as well as the population adopting a low-salt diet, significantly contribute to reducing salt intake, chronic diseases, and social security expenditures. By the year 2040, implementing measures such as expediting the promotion of low-salt diets among the population is expected to decrease the total number of individuals affected by CVD to approximately 18 million and CKD to 21 million. This would incur medical care costs of 28 trillion yen and long-term care costs of 34 trillion yen. Alternatively, voluntary food reformulation could decrease the CVD population to around 13 million and CKD population to 9 million, resulting in total medical care expenditures of 16 trillion yen and long-term care expenditures of 19 trillion yen. Furthermore, aggressive salt intake reduction interventions through mandatory food reformulation could potentially decrease the number of CVD and CKD populations by 2040 to 13 million people and 8 million people, covering medical care costs and long-term care costs of approximately 15 trillion yen and 18 trillion yen, respectively. Hence, Japan's endeavor to mitigate salt intake by implementing strategies such as promoting low-salt diets among the population and food reformulation, particularly through mandatory reformulation measures, is likely to confer significant public health benefits.

INTRODUCTION

Globally, non-communicable diseases (NCDs) like cardiovascular diseases, cancer, and type 2 diabetes are on the rise, accounting for an estimated 41 million deaths annually, which represents 74% of all global deaths [1]. In 2017, it was estimated that 3 million NCD-related deaths were linked to high sodium intake, making it the leading dietary risk factor for deaths worldwide [2]. In Japan specifically, high salt intake is identified as the primary dietary risk factor contributing to NCDs such as stomach cancer, cardiovascular diseases (CVD), and chronic kidney disease (CKD) [3]. Consequently, the World Health Organization (WHO) has called for a 30% reduction in the average sodium intake of the population by 2025 [4], recommending that salt intake should not exceed 5g per day [5].

Despite global efforts to reduce salt consumption, salt intake levels in Japan remain high, with over half of the population consuming more than the recommended daily amount. According to the INTERMAP study [6], the average salt intake among Japanese individuals is 11.6 grams per day, prompting the Japanese government to prioritize salt intake reduction in its health policy agenda. The Japanese national health promotion plan, referred to as Health Japan for its second and third phases, aims to decrease salt consumption to 8 grams per day for Japanese adults by 2022 [7] and further reduce it to 7 grams per day by 2032 [8]. Achieving this goal requires a collaborative effort among multiple stakeholders, including the food industry, which has made significant strides in offering low-salt options [9]. In 2017, the WHO recommended sodium reduction through food product reformulation to lower sodium content, considering it a cost-effective and feasible intervention for preventing NCDs [10]. Consequently, various countries [11–16], including Japan [17] have focused on sodium reduction interventions that involve food companies reformulating their products to contain less sodium. For example, the Japanese Society of Hypertension has incentivized the food industry to reduce salt content in processed foods by recognizing companies that significantly reduce salt while maintaining favorable taste for consumers. This initiative has reduced around 8,530 tonnes of salt in processed and seasoning products [18]. However, beyond food reformulation efforts are needed to promote healthy population consumption patterns. For a meaningful impact, reduced-salt products must be accompanied by consumer adoption of reduced-salt diets [19].

Therefore, this research sought to examine the impact of salt reduction interventions through food product reformulation by companies and population’s adopting low-salt food diets on the average dietary salt intake, the prevalence of chronic diseases, and the social care costs related to chronic diseases attributed to salt consumption in Japan.

RESEARCH GAP AND ORIGINALITY

Academic interest has been sparked by attempts to decrease sodium/salt consumption, prompting extensive scholarly and public-private discussions. This interest stems from the adverse effects of high salt intake on public health and the social security expenses of nations. Numerous previous studies have examined the potential health and financial implications of salt consumption, employing various simulation methodologies in countries such as Japan [20, 21] and others [22–24]. Among these studies, only one in Japan [21] has utilized system dynamics methodology to analyze the cardiovascular effects of salt intake reduction.

Although system dynamics has been effectively applied in healthcare, health and social policies, the method also has gained increasing interest in epidemiological research including the evaluation of interventions for managing CVD and CKD. Noteworthy examples include the Prevention Impacts Simulation Model (PRISM) [25], a system dynamics simulation model was designed to assess the effects of CVD risk factors. The adoption of system dynamics for epidemiological research is thus on the rise, with PRISM model being implemented in countries like New Zealand [26] and Singapore [27, 28], where it has been expanded to evaluate the impact of various CVD intervention policies [29–32].

Based on the preceding discussion, to the best of our knowledge, there is no analogous system dynamics model for evaluating the potential health and financial gains resulting from both initiatives by food companies and population-driven efforts. Consequently, this study diverges from previous modeling studies in several significant aspects. First, it presents a model that assesses interventions aimed at reducing salt intake, including food companies' product reformulation and the Japanese population's adoption of low-salt diets and the reduced-salt products. Second, it focuses on major chronic diseases attributed to high salt consumption, such as CVD and CKD in Japan. Third, it integrates associated social security costs, including medical and long-term care costs in Japan.

METHODOLOGY

System Dynamics Model

System dynamics simulation is a method used to comprehend the behavior of complex systems over time. It emphasizes that a system's structure and the interactions between its elements through nonlinear feedback loops determine its behavior. Grasping both the structure and behavior of a system is vital for problem-solving, simulating different scenarios, predicting outcomes, and devising effective strategies. Consequently, the technique assists researchers and decision-makers in understanding how changes determine the system's structure and making appropriate plans. Generally, system dynamics exhibit both qualitative and quantitative characteristics. The qualitative aspect relies on constructing causal loop diagrams (CLDs), which are simple representations of causal relationships between various factors [33]. On the other hand, the quantitative aspect involves stock and flow diagrams (SFDs), which illustrate how components of a system interact and influence its behavior over time using graphical icons. In SFDs, a "stock", depicted by box-shaped icon, represents state variables within the system that change over time, such as number of citizens in a country or water in a reservoir. A "flow", indicated by double arrows entering and exiting the stock variable, symbolizes the movement of entities into and out of the stock. In the context of our epidemiological case study, a stock represents the accumulation of disease prevalence, while the inflow to the disease stock variable represents the incidence rate, and the outflow represents deaths due to the disease or recovery from the disease.

Model Conceptualization

The proposed model framework in Figure 1 explores the intricate causal relationships between salt intake reduction interventions, including food reformulation by companies and the adoption of low-salt diet among the population, and their impact on various health and economic outcomes in Japan. In salt intake reduction intervention model encompasses two main strategies namely product reformulation by food companies to reduce salt content in their products and initiatives aimed at encouraging the adoption of low-salt diet among the population. The primary outcome variable of interest is the average dietary salt intake among the Japanese population that shown in the salt intake model. This variable is influenced by both food reformulation efforts and the adoption of low-salt diet behavior. The disease model considers the incidence and prevalence of three kinds of salt-attributed illnesses, with a focus on hypertension, CVD and CKD. The final model is expenditures of social security model that evaluates the economic implications of salt intake reduction interventions on social security costs, particularly medical care expenditure and long-term care expenditure. Reduction in disease prevalence and associated medical and long-term care costs are expected outcomes of successful salt intake reduction efforts.

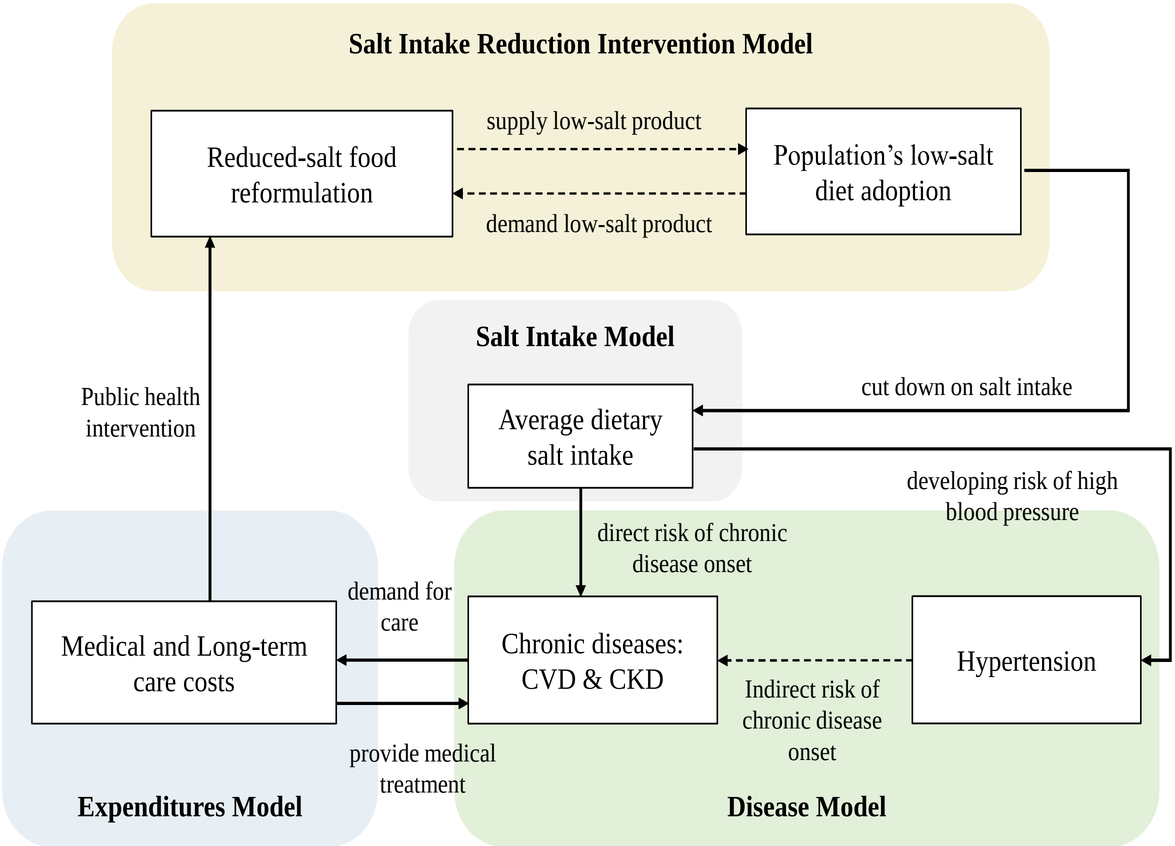

Figure 1. Model overview of salt intake reduction intervention

Causal Loop Diagram

The causal loop diagram in Figure 2 demonstrates the feedback loops and interconnections within a system aimed at reducing dietary salt intake through interventions like product reformulation and the adoption of low-salt products and diets by the population. The R1 and R2 loops highlight the role of product reformulation by the food industry and the adoption of low-salt products and diets, respectively. As the industry reduces salt content in its products via reformulation, it expands the availability of low-salt food choices in the market. With greater availability and accessibility, people are more likely to purchase and consume these options, thereby increasing overall consumption of low-salt products. This increased consumption fosters wider adoption of low-salt diets across the population. As consumer demand for low-salt products grows, the food industry is incentivized to continue reformulating products to meet this growing demand, thus reiforcing the cycle.

The B1 loop explores how policies and programs designed to decrease salt consumption are pivotal in enhancing health education and awareness. Public health campaigns that promote the benefits of a low-salt diet increase understanding about the hazards associated with excessive salt intake. As these awareness efforts effectively inform people, they are motivated to cut back on salt, leading to a greater market demand for low-salt products. This shift results in lower overall dietary salt consumption, which reduces the risk of high blood pressure and lowers the incidence of chronic diseases, ultimately strengthening public health initiatives.

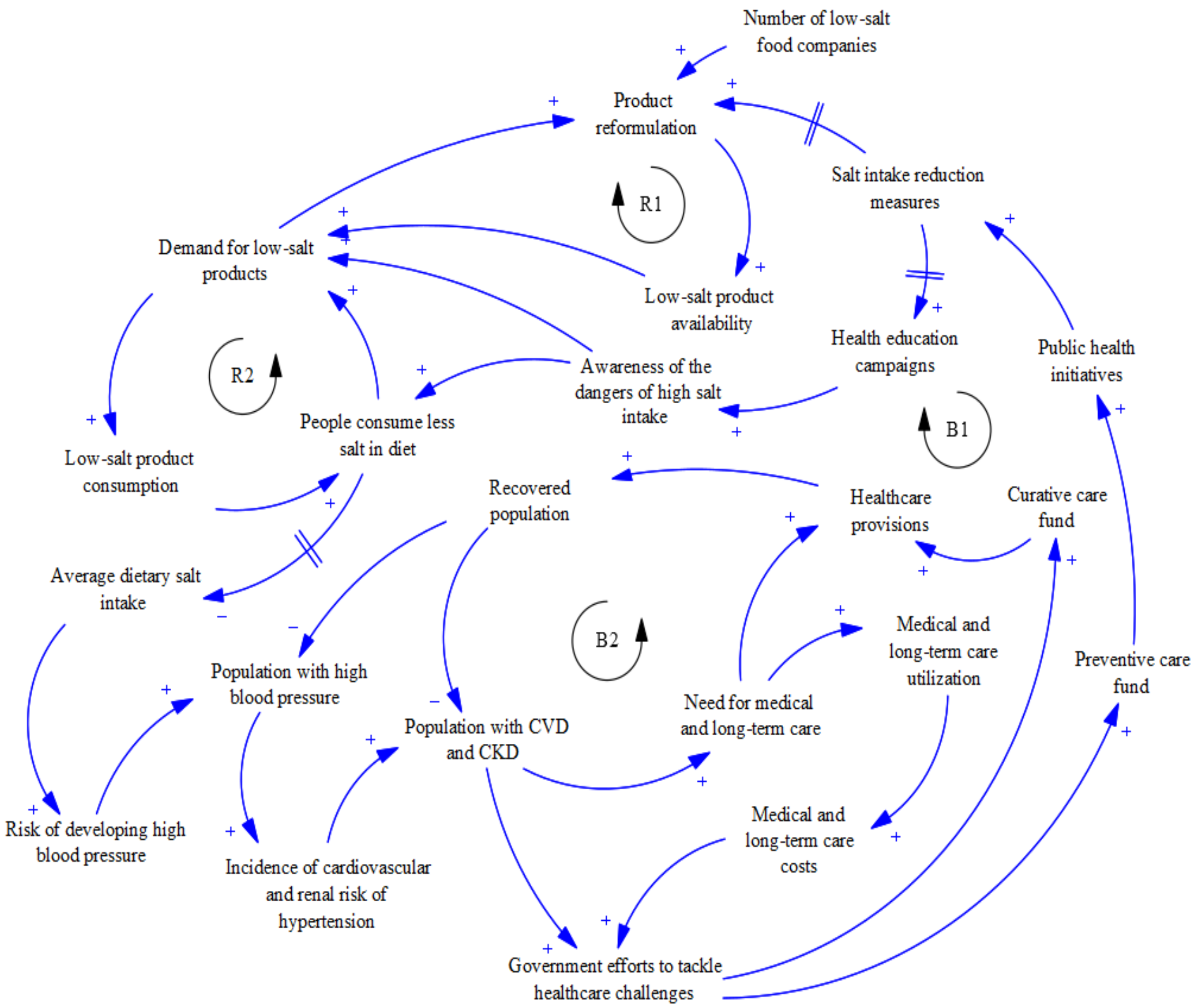

Figure 2. Simplified causal loop diagram of salt intake reduction intervention

The B2 loop looks at how disease prevalence and economic impact are interconnected. Excessive salt intake leading to high blood pressure increases the incidence of chronic conditions such as CVD and CKD, resulting in higher medical and long-term care expenditures. The rising prevalence of chronic diseases prompts government to address health challenges by allocating a significant portion of the social security budget to both curative and preventive healthcare. Increased funding for medical care enables more patients to receive treatment, reducing the population affected by salt-related diseases. Concurrently, increased funding for preventive healthcare supports health promotion and public health campaigns aimed at lowering average salt consumption and other healthy dietary practices. As preventive measures take hold, disease burden could lessens, mitigating economic strain by reducing healthcare costs. Hence, these loops help us to understand how addressing blood pressure through salt reduction can alleviate financial pressures on healthcare systems.

Stock and Flow Diagram

In this comprehensive simulation model, we integrated four interconnected sub-diagrams: dietary salt intake, prevalence of chronic diseases, social security expenses, and interventions for reducing salt intake. These sub-diagrams were developed based on the simplified causal loop diagram discussed in the preceding section. To build the simulation model, we reviewed and applied a wealth of the current issues and available literatures on modifiable risk factors for CVD and CKD, such as excessive dietary salt intake and hypertension (HTN), as well as interventions to prevent the occurrence of these diseases, including food reformulation and the adoption of low-salt diet among the population. The entire model was implemented using the simulation software Vensim DSS 10.1.1. Our model has about 130 parameters in all.

Dietary Salt Intake Model

The dietary salt intake model shown in Figure 3 illustrates the dynamics of salt consumption. The average dietary salt intake is 10.4 grams [34], while the salt intake target is set at 8 grams in accordance with the second term of Health Japan 21's dietary goal [7]. The components within this model can be mathematically represented as follows:

$$Na_{\tau} = Na_{t=0} + \Delta Na \tag{1}$$

$$\Delta Na = \frac{Ratio_{Na} \times A_{LSD} \times Discrepancy_{Na}}{AT_{\Delta Na}} \tag{2}$$

$$Ratio_{Na} = \frac{Perceived_{Na}}{Na} \tag{3}$$

$$Discrepancy_{Na} = Target_{Na} - Na \tag{4}$$

where Na_{τ} represents the current average dietary salt intake. It is determined by its initial state ($Na_{t=0}$) and its inflow which is change in salt intake (ΔNa) as expressed in equation (1) explaining, the result of action or effort to decrease salt intake. The variable ΔNa is influenced by the ratio of perceived and actual mean salt intake ($Ratio_{Na}$), proportion of individuals adopting low-salt diet (A_{LSD}), the discrepancy between the target salt intake and the actual mean salt intake ($Discrepancy_{Na}$) and the average time taken to change in salt intake ($AT_{\Delta Na}$), as depicted in equation (2). Equation (3) expresses $Ratio_{Na}$ as the division of perceived salt intake ($Perceived_{Na}$) by the actual salt intake (Na). In equation (4), $Discrepancy_{Na}$ calculates the difference between the salt intake target ($Target_{Na}$) and the average dietary salt intake specified in 2012 (Na). $AT_{\Delta Na}$ is adjustment time to change salt intake which is explaining the average time required for the population to modify their eating patterns, such as lowering salt intake and sugary beverage consumption [35]. This model specifically includes the linked variable from salt intake reduction intervention, A_{LSD} to examine the impact of adopting a low-salt diet on country's average dietary salt intake. Our hypothesis posited that an increased number of individuals adopting low-salt diets would lead to a reduction in salt intake among the population.

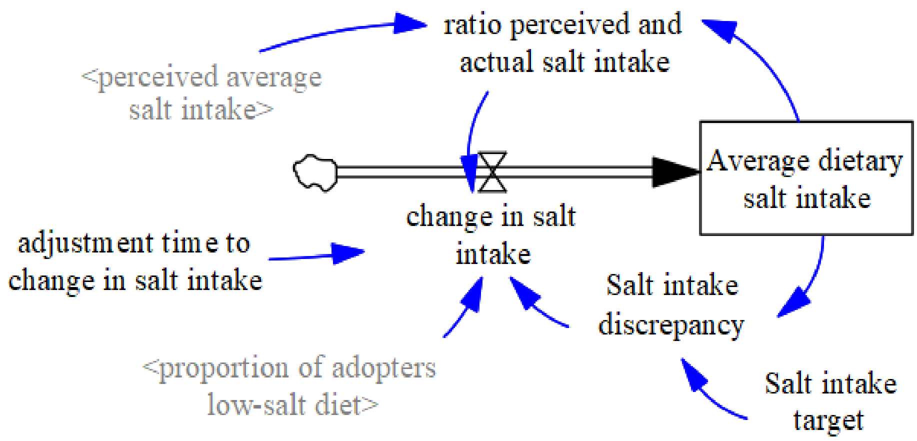

Figure 3. Dietary salt intake model

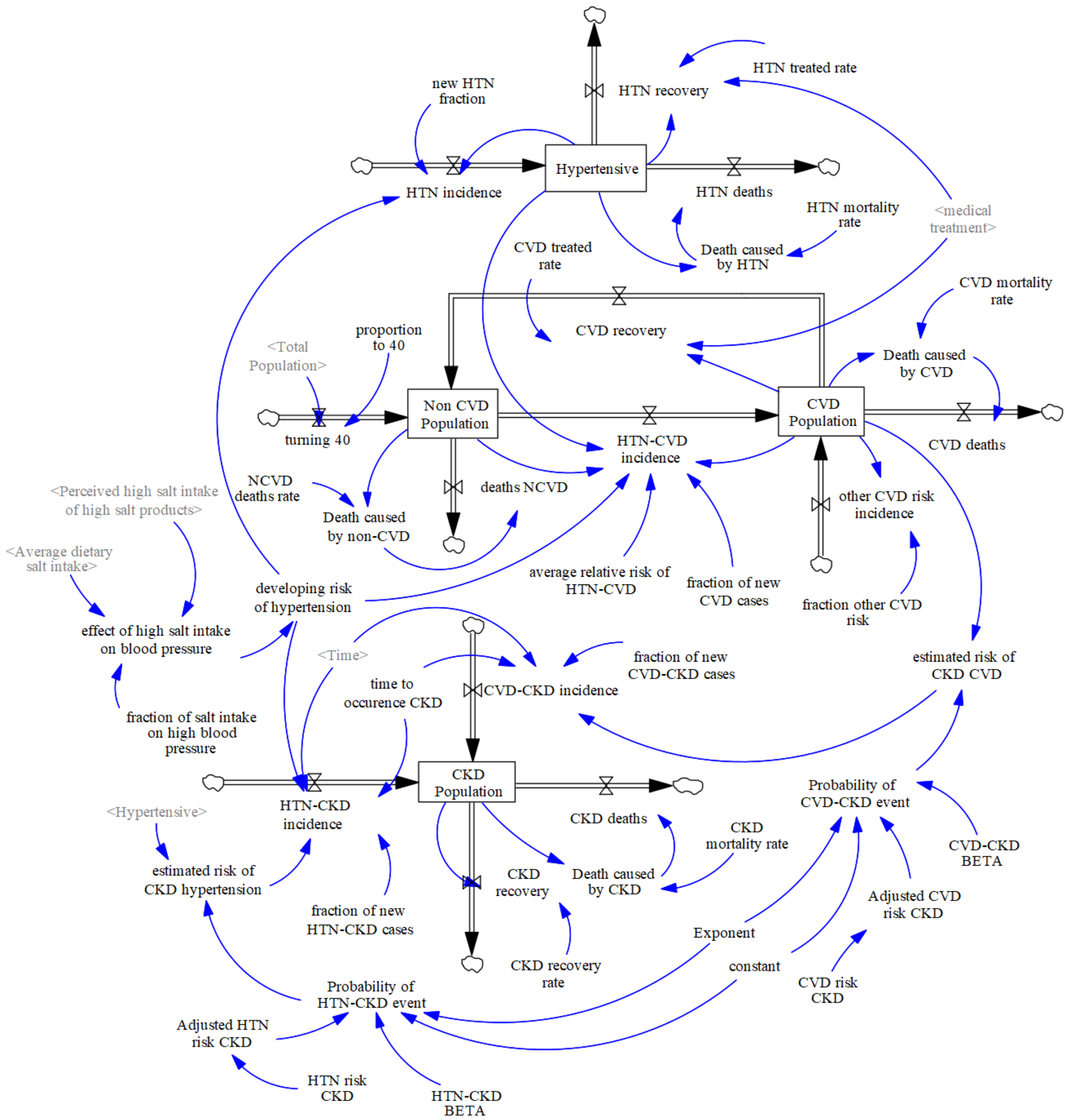

Figure 4. Disease prevalence model

Chronic Disease Model

Figure 4 depicts the underlying framework for chronic disease prevalence. This epidemiological model includes three major illnesses linked with high salt consumption: HTN, CVD, and CKD, which are represented by stock boxes. Each disease population stock is also linked by flows in and out, determining the cumulative values within each stock over time. We simplified the model used in previous research [27, 28] to build our disease epidemiology model. This disease model shows how dietary salt consumption affects disease prevalence by developing raised blood pressure, which is one of the major metabolic risk factors that contribute to the increased risk of CVD and CKD. A large number of epidemiological evidence prove that HTN is a major risk factor for cardiovascular disease, chronic kidney damage and death [36, 37]. Aburto et al. [38] for instance, found that high dietary salt levels increase people's risk of HTN, as well as CVD. Consequently, this model assists us visualising the link between dietary salt consumption and disease prevalence.

Generally, an individual diagnosed with HTN is characterized by having a mean systolic blood pressure equal to or greater than 140 mmHg and/or a mean diastolic blood pressure greater than or equal to 90 mmHg and/or the use of antihypertensive medication [34]. The hypertensive population grows due to HTN incidence (I_{HTN}) and declines through deaths (D_{HTN}) and recovery from HTN (R_{HTN}). Specifically, I_{HTN} is calculated from the multiplication of hypertensive population (*HTN*), risk of developing HTN ($Risk_{HTN}$) and fraction of new HTN cases (new_{HTN}). Death of HTN (D_{HTN}) is calculated as HTN multiply rate of mortality due to HTN ($mortality_{HTN}$) as shown in equation (7). While, recovery from HTN is influenced by individuals undergoing medical treatment at healthcare facilities (mt) and the fraction of individuals who experience recovery ($treated_{HTN}$) as expressed in equation (8). Both calculation for death and recovery of diseases variables are also applied to the rest parts of disease models such as CVD and CKD.

$$HTN_\tau = HTN_{t=0} + (I_{HTN} - D_{HTN} - R_{HTN}) \tag{5}$$

$$I_{HTN} = HTN \times Risk_{HTN} \times new_{HTN} \tag{6}$$

$$D_{HTN} = HTN \times mortality_{HTN} \tag{7}$$

$$R_{HTN} = HTN \times treated_{HTN} \times mt \tag{8}$$

Furthermore, CVD sub-model divides the population into two distinct health states: the non-CVD population, consisting of individuals who have never experienced a cardiovascular disease (CVD) event, and the CVD population, comprising individuals who have had CVD events. This sub-model illustrates the transition of certain individuals from a non-cardiovascular health state to a cardiovascular health state, elucidating how those initially classified as non-cardiovascular eventually become part of the cardiovascular population. Equation (9) expresses that the current non-CVD population ($NCVD_\tau$) increases due to the proportion of individuals reaching the age of 40 ($Turn40$) and the proportion of individuals recovering from CVD (R_{CVD}), while it decreases due to deaths from non-CVD (D_{NCVD}) and the incidence rate of CVD resulting from HTN risk (I_{HTNCVD}). The current CVD population (CVD_τ) increases as a result of the rate of CVD caused by HTN (I_{HTNCVD}) and incidence of CVD caused by other risk factors ($I_{NHTNCVD}$). In simple terms, our CVD sub-model attempts to show that higher blood pressure levels are linked to a greater risk of CVD. On the other hand, CVD_τ decreases due to deaths (D_{CVD}) and recovery (R_{CVD}) from CVD, indicated by the transition flow-out from the CVD population back to the non-CVD state population, as expressed in equation (10). Equation (11) delineates the calculation of incidence of HTN risk attributed to CVD (I_{HTNCVD}), which is determined by several elements, such as non-CVD population ($NCVD$), hypertension risk ($Risk_{HTN}$), average cardiovascular disease risk in hypertensive individuals (ar_{HTNCVD}), the fraction of new cardiovascular disease cases (new_{CVD}) and the proportion of hypertension within the cardiovascular disease population ($\frac{HTN}{CVD}$).

$$NCVD_{\tau} = NCVD_{t=0} + (Turn40 + R_{CVD} - D_{NCVD} - I_{HTNCVD}) \quad (9)$$

$$CVD_{\tau} = CVD_{t=0} + (I_{HTNCVD} + I_{NHTNCVD} - R_{CVD} - D_{CVD}) \quad (10)$$

$$I_{HTNCVD} = NCVD \times Risk_{HTN} \times ar_{HTNCVD} \times new_{CVD} \times \frac{HTN}{CVD} \quad (11)$$

where, both $NCVD_{t=0}$ and $CVD_{t=0}$ denote the initial non-CVD population and the initial CVD population, respectively.

In the CKD sub-models, we utilized the Framingham risk engine calculation [39, 40] to predict the likelihood of CKD events based on the risk factors. Due to data constraints of acquiring data glomerular filtration rate (GFR), that usually used to define CKD and further to calculate different stages of CKD as developed in other study [28, 41], our study used cumulative number of CKD prevalence in Japan that is identified as one stock variable of CKD population in CKD sub-model. In our simplified CKD sub-model, we presumed that the probability of CKD events is influenced by two distinct risk groups: the HTN risk group and the CVD risk group, which are represented mathematically as follows:

$$CKD_{HTN} = \frac{1}{1+e^{-(\alpha_0 + \alpha_1 HTNriskCKD)}} \quad (12)$$

$$CKD_{CVD} = \frac{1}{1+e^{-(\beta_0 + \beta_1 CVDriskCKD)}} \quad (13)$$

Concerning our model variables and equations (12) and (13), the intercepts α_0, and β_0 represent the HTN-CKD BETA and CVD-CKD BETA, respectively. Meanwhile, the coefficients α_1, and β_1 represent the adjusted HTN risk and adjusted CVD risk for CKD, respectively. Following equations (14) to (16) are to estimate some major variables in CKD sub-models:

$$CKD_{\tau} = CKD_{t=0} + (I_{HTNCKD} + I_{CVDCKD} - R_{CKD} - D_{CKD}) \quad (14)$$

$$I_{HTNCKD} = \frac{r_{\widehat{HTNC}KD} \times Risk_{HTN} \times Time \times new_{HTNCKD}}{TO_{CKD}} \quad (15)$$

$$I_{CVDCKD} = \frac{r_{\widehat{CVDC}KD} \times Time \times new_{CVDCKD}}{TO_{CKD}} \quad (16)$$

where, CKD_τ is current CKD population, $CKD_{t=0}$ is initial CKD population, I_{HTNCKD} is incidence of HTN risk attributed to CKD, I_{CVDCKD} is incidence of CVD risk attributed to CKD, R_{CKD} is recovery CKD, $r_{\widehat{HTNCKD}}$ is estimated HTN risk of CKD, new_{HTNCKD} is fraction of new cases of CKD in HTN population, TO_{CKD} time to occurrence CKD, $r_{\widehat{CVDCKD}}$ is estimated CVD risk of CKD, and new_{CVDCKD} is fraction of new cases of CKD in CVD population.

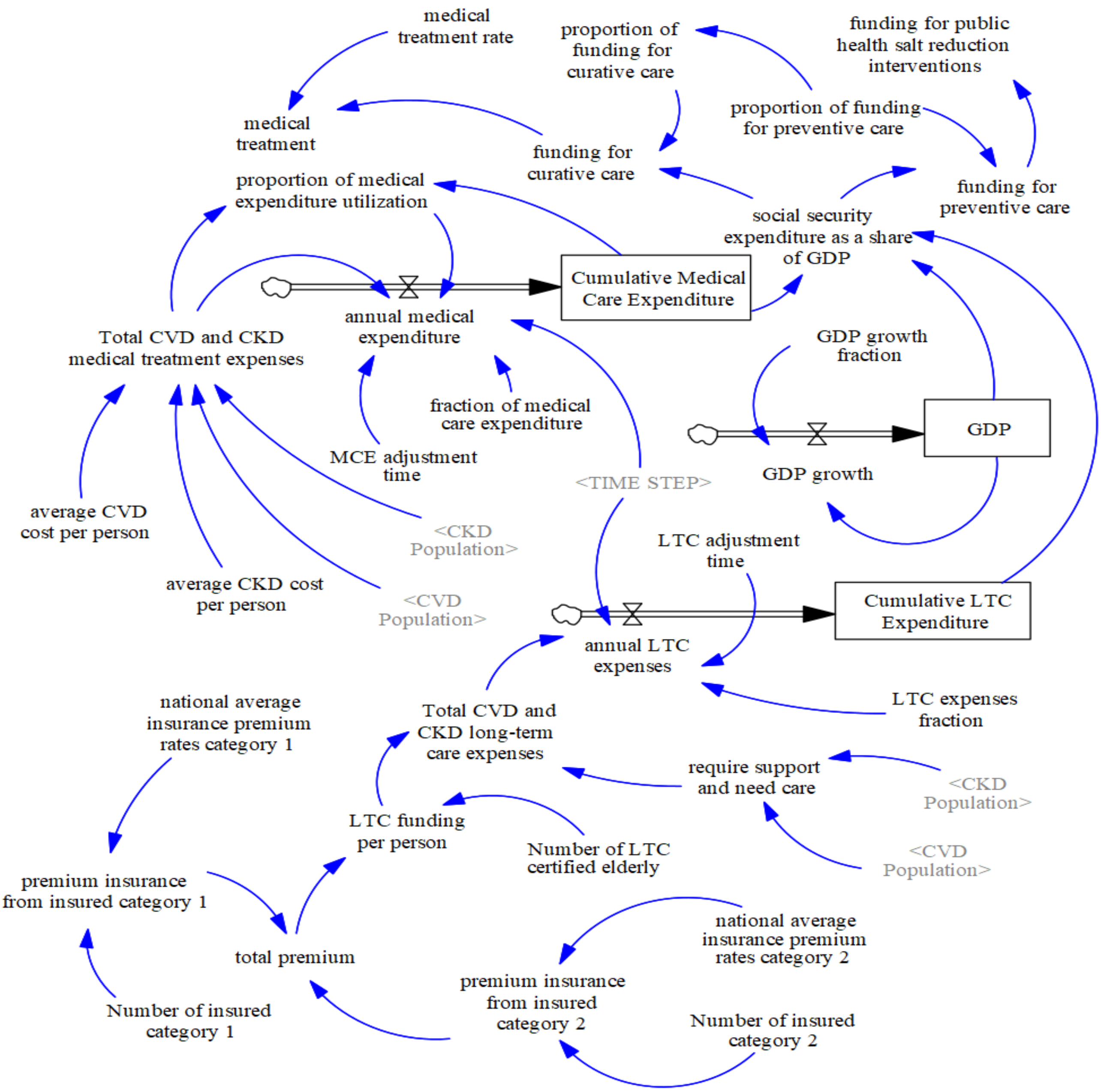

Figure 5. Social security expenditure model

Social Security Expenditure Model

Complications arising from CVD and CKD, along with their associated treatment costs, impose a significant burden on both society and the healthcare system in Japan. Figure 5 illustrates the framework of medical and long-term care costs contributing to the overall societal cost of the chronic disease population. The annual medical expenditure rises with an increase in the number of CVD and CKD patients requiring treatment, particularly formulated in the following equation:

$$\Delta MCE = \frac{MTE_{CVDCKD} \times TIME\ STEP \times \%\ MCE\ utilization \times MCE\ fraction}{AT_{MCE}} \quad (17)$$

where the growth rate of annual medical care expenditure (ΔMCE) impacts the cumulative stock of medical care expenditure. MTE_{CVDCKD} represents the total medical treatment expenses for both CVD and CKD, accounting for costs incurred by individuals with these health conditions and their associated unit cost per patient. Meanwhile, $\%\ MCE\ utilization$ signifies the proportion of total medical expenses allocated to both CVD and CKD relative to the cumulative national medical care expenditure. Both the $MCE\ fraction$ and AT_{MCE} denote the percentage change in medical care expenditure and its adjustment time, respectively.

The aging population in Japan has led to a rise in the number of individuals needing long-term care, especially among those with chronic diseases and limited self-management abilities. Our LTC expenditure sub-model illustrates how funding and benefit expenses in LTC significantly influence total LTC expenditure. LTC fund primarily comes from premium payments made by LTCI participants each month, with participants categorized into Category 1 (aged 65 and older) and Category 2 (aged 40 to 64), each subject to different premium rates as per LTCI regulations [42]. Non-premium funding, such as grants and investments, is not considered in our study as it falls outside our scope. The funding from LTCI is used to cover a range of care-related expenses. As the number of patients increases, costs also rise, thereby affecting overall expenses. Therefore, treating illnesses results in expenses for social security expenditure. Growth in the annual LTC expenditure ($\Delta LTCE$) can be calculated as follows:

$$\Delta LTCE = \frac{LTCE_{CVDCKD} \times TIME\ STEP \times LTCE\ fraction}{AT_{LTCE}} \quad (18)$$

where $LTCE_{CVDCKD}$ represents the total long-term care expenses for both CVD and CKD, accounting for costs incurred by elderly with these health conditions who need LTC support and care and funded costs per individual. Both the $LTCE\ fraction$ and AT_{LTCE} denote the percentage change in long-term care expenditure and its adjustment time, respectively.

Moreover, this spending model also illustrates the allocation of social security (both medical and long-term care) expenditures to two types of care, namely preventive care and curative care. The share of social security costs dedicated to preventive care is presumed to fund public health interventions, including salt reduction strategies such as media campaigns, connected to the subsequent salt intake reduction intervention sub-model. On the other hand, the portion of social security costs allocated to curative care is assumed to cover medical treatments for chronic disease patients, thereby contributing to the percentage of patients recovering from each specific disease.

Salt Intake Reduction Intervention Model

In essence, our salt intake reduction intervention model in Figure 6 is an adaptation of previous study on salt reduction in Japan [43] and expansion of a generic diffusion model like the infectious disease transmission model, and Bass innovation diffusion model. This salt intake intervention model delineates the co-flow structure of two categories within the adoption model: population adoption of a low-salt diet and food companies adopting food reformulation to reduce salt content in their products. Within the sub-model of population adoption of a low-salt diet, shown on the upper part of the diagram, two primary stocks are identified: potential adopters (PA_{LSD}) and adopters (A_{LSD}). Potential adopters, also referred to as individuals who are aware of the need to reduce salt intake in their diets, represent the current number of people who have not yet adopted a low-salt diet. Consumers with greater knowledge about dietary salt are more likely to purchase salt-reduced food products and exhibit readiness to alter their dietary salt intake, owing to the motivational effect of this knowledge and its facilitation of information processing regarding salt-related label information [44]. Therefore, this stock variable is influenced by the awareness rate, which is derived from public health intervention campaigns related to salt intake, and is also contingent upon the proportion of social security expenditure allocated to public health intervention. Currently, Japan allocates only 3% of its expenditure to preventive care compared to curative care [45].

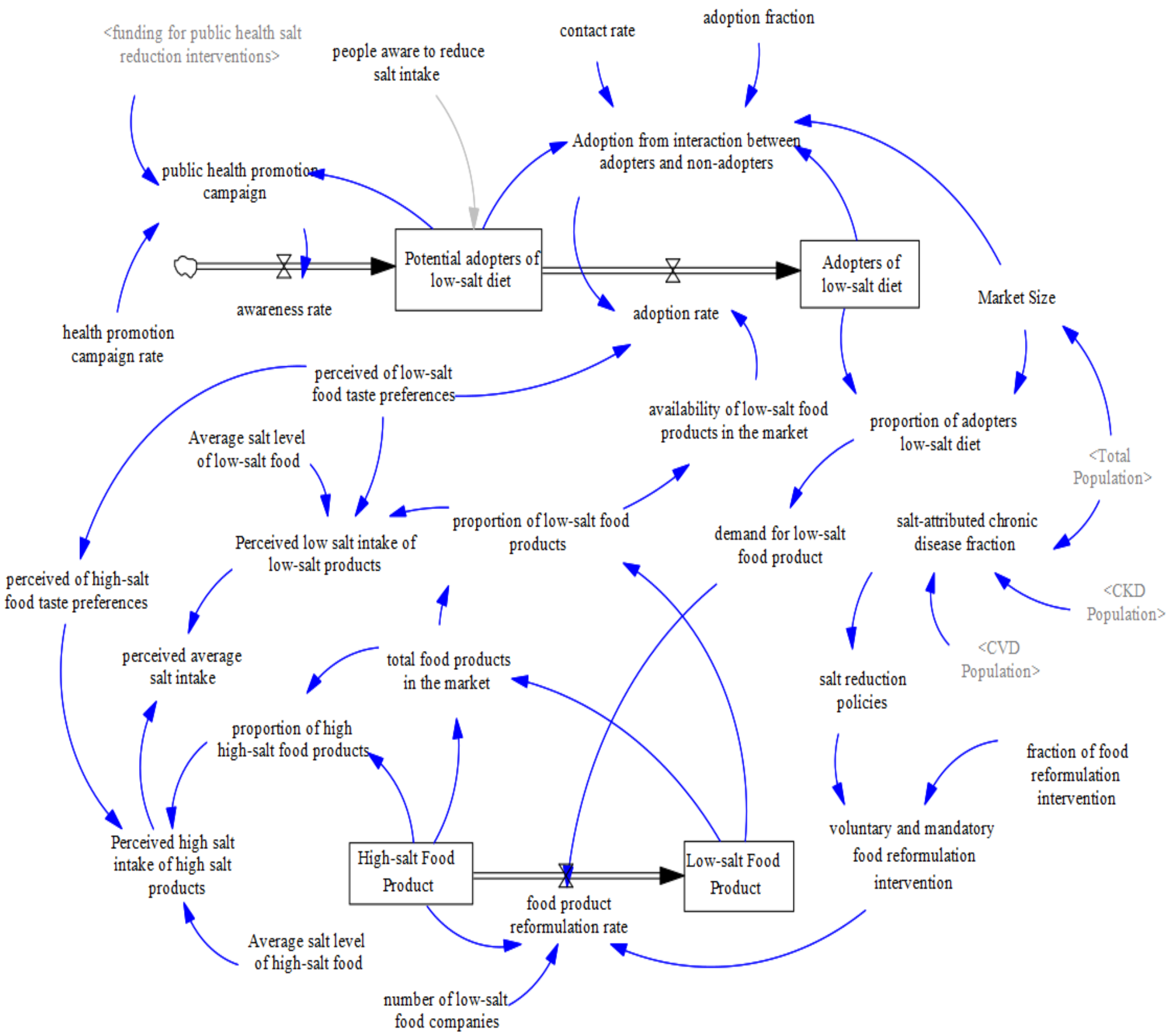

Figure 6. Salt intake reduction intervention model

Meanwhile, adopters are individuals who have already embraced a low-salt diet or those who naturally consume less salt than the average intake. Potential adopters transition to becoming adopters of a low-salt diet when they encounter individuals who have already adopted this behavior, reflecting the impact of word-of-mouth communication within the population, as denoted by "adoption from interaction between adopters and non-adopters" in the model. This variable is determined by the contact rate (c) and adoption fraction (af) variables. The contact rate represents how much influence adopters exert on the adoption rate, indicating the number of potential adopters persuaded by each adopter to adopt a low-salt diet within a specific timeframe. On the other hand, the adoption fraction refers to the proportion of times when a contact between an active adopter and a potential adopter leads to adoption. We assume that the likelihood of adoption, given a contact between a potential and an adopter, is 4%. Thus, this imitation effect influences the adoption rate, affecting the inflow rate into the adopters of low-salt diet stock. Additionally, we assume that the adoption rate is influenced by perceived taste preferences for low-salt foods and the availability of low-salt food products in the market, which are linked from the lower sub-model of the diagram. This sub-model can be mathematically expressed as:

$$WOM_{LSD} = PA_{LSD} \times c \times af \times \frac{A_{LSD}}{MS} \tag{19}$$

$$AR_{LSD} = WOM_{LSD} \times SS_{LSP} \times taste_{LSP} \tag{20}$$

where WOM_{LSD} stands for word-of-mouth that referring to the variable of "adoption from interaction between adopters and non-adopters" (AR_{LSD}). Parameter MS, SS_{LSP}, and $taste_{LSP}$ refer to market size which is the current total population, availability of low-salt food products in the market and perceived of low-salt food taste preferences, respectively. This adoption effect highlights two phenomena: (1) the impact of changes in the number of potential adopters on the adoption rate, thereby influencing the balance of potential adopters, and (2) how changes in the adoption rate leads to corresponding changes in the number of adopters, resulting in an exponential impact.

The bottom part of Figure 6 represents food product reformulation by food companies to reduce the salt content in their high-salt food products. This sub-model comprises two stock variables: high-salt food products and low-salt food products. The model assumes that the transition from high-salt content food products to low-salt content food products, indicated by the flow rate labeled as "food product reformulation rate" is influenced by the demand for low-salt food products, the number of low-salt food companies, and the fraction of reformulating products. In relation to the previous low-salt diet adoption model, an increase in the number of people adopting low-salt diet is expected to increase the demand for low-salt products, thereby influencing food product reformulation by food companies. Health conditions also drive food manufacturers to reformulate their products in response to government policies aimed at reducing salt and improving the healthfulness of food products to enhance health and nutrition outcomes [46]. This food reformulation sub-model can be mathematically expressed as:

$$FR_{LSP} = DD_{LSP} \times HSP \times Companies_{LSP} \times Intervention_{FR} \tag{21}$$

where FR_{LSP} is food product reformulation rate, DD_{LSP} is demand for low-salt food product, HSP is the number of high salt food products, $Companies_{LSP}$ is the number of low-salt food product companies and $Intervention_{FR}$ is refer to variable of food reformulation intervention.

Data and Study setting

Table 1. Parameter value for the key variables

Parameters	Unit	Initial value	Sources
Average dietary salt intake per day	Gram	10.4	[34]
Salt intake target	Gram	8	[7]
Total population	People (Thousand)	127,515	[47]
CVD population	People	13,489,825	[48]
CKD population	People	18,678,724	[48]
Number of low-salt food products	Product	34	[18]
Number of low-salt food companies	Dmnl	12	[18]
Health promotion campaign	Dmnl	0.02	[49]
People aware to reduce salt intake	People	94,998,675	[50]
Cumulative medical care expenditure	Yen (Hundred million)	392,117	[51]
Cumulative long-term care expenditure	Yen (Million)	8,641,640	[52]
Gross domestic product	Yen (Hundred million)	4,994,239	[53]

The model was developed to cover the period from 2012 to 2040, with a time step of 0.0625. The target population concentrated on the adult population aged 40 and above in Japan, based on data from the statistics bureau of Japan [47]. Both literature reviews and publicly available datasets were utilized to refine the parameters in the model. Time series datasets for disease prevalence, medical costs and long-term care costs were obtained from the Institute for Health Metrics and Evaluation [48] and Japan's Official Statistical online database [51, 52]. Other auxiliary and constant variables were derived from literature and model calibration. The input parameters of the main variables and data sources are listed in Table 1. These parameters were applied in the initial steady state of our model.

Model validation test

Several validation tests are recommended in system dynamics to establish confidence in the model structure [54]. To maintain brevity, this study employed structure-based validation and behavior reproduction validation tests to ensure the suitability of the model for its intended purpose and to verify its validity. In structure-based validation, the dimensional consistency test of the model equations and all variables were examined. If the units are accurate, the model is deemed validated [54]. Therefore, the unit checking test and the function of 'model check' conducted by Vensim DSS 10.1.1 software confirmed the validation of our model as the software shows no unit error, indicating that the unit is consistent across the model.

This study then examined extreme-condition test to determine the structure's validity. An extreme-condition test is assigning an extreme value to a particular parameter and comparing model-generated behavior to observed behavior of the real system under the same 'extreme condition'. The purpose of the extreme condition test is to evaluate if each equation makes sense even when its inputs take on extreme values and to guarantee the model responds plausibly when subjected to extreme shocks and parameter values [54]. The test also assesses the model's robustness, as the model should react in a realistic manner regardless of how extreme the inputs or policies imposed on the model are [54]. In this experiment, we set the initial value of key variables of the salt reduction intervention model, such as food reformulation and low-salt diet adopters, to zero at the state we assume of "no salt intake intervention".

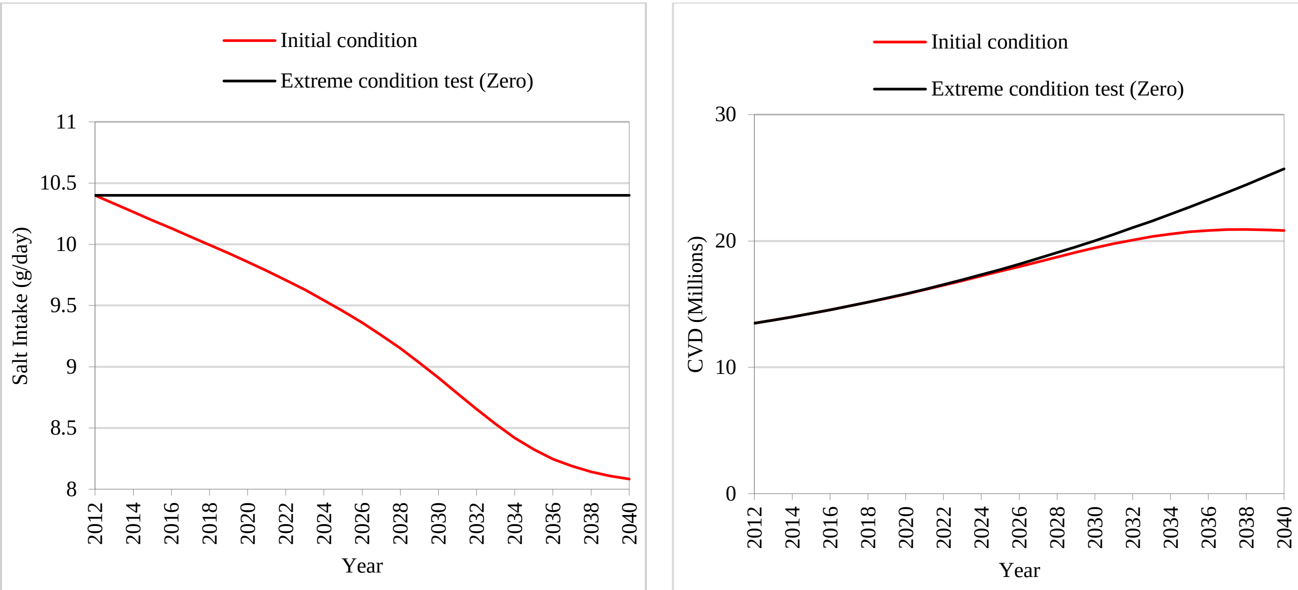

Figure 7. Behaviour of initial and extreme conditions tests

Figure 7 presents the results of extreme condition tests for dietary salt intake and CVD population. The solid black line represents our hypothetical assumption that if salt intake reduction measures were not implemented, in comparison to our model's baseline condition. According to these findings, the average dietary salt intake would remain at 10.4 grams per day throughout the simulated period until 2040. As a result, there would be an increase in the number of individuals affected by CVD. This outcome is due to the absence of individuals influencing potential adopters to adopt low-salt diet and no initiative to reformulate the food products, resulting in zero adoption and reformulation rates. Consequently, with no net flow, both the stocks of low-salt food products and low-salt diet adopters remain stagnant at zero. Therefore, without initiatives from both food companies and the population to reduce salt intake, the country's average dietary salt intake would remain unchanged, leading to persistent increase in disease prevalence and a continued rise in medical and long-term care costs borne by the government and society. Hence, conducting this test allows us to understand the rationale behind the introduction of salt intake reduction interventions to reduce average dietary salt intake among population.

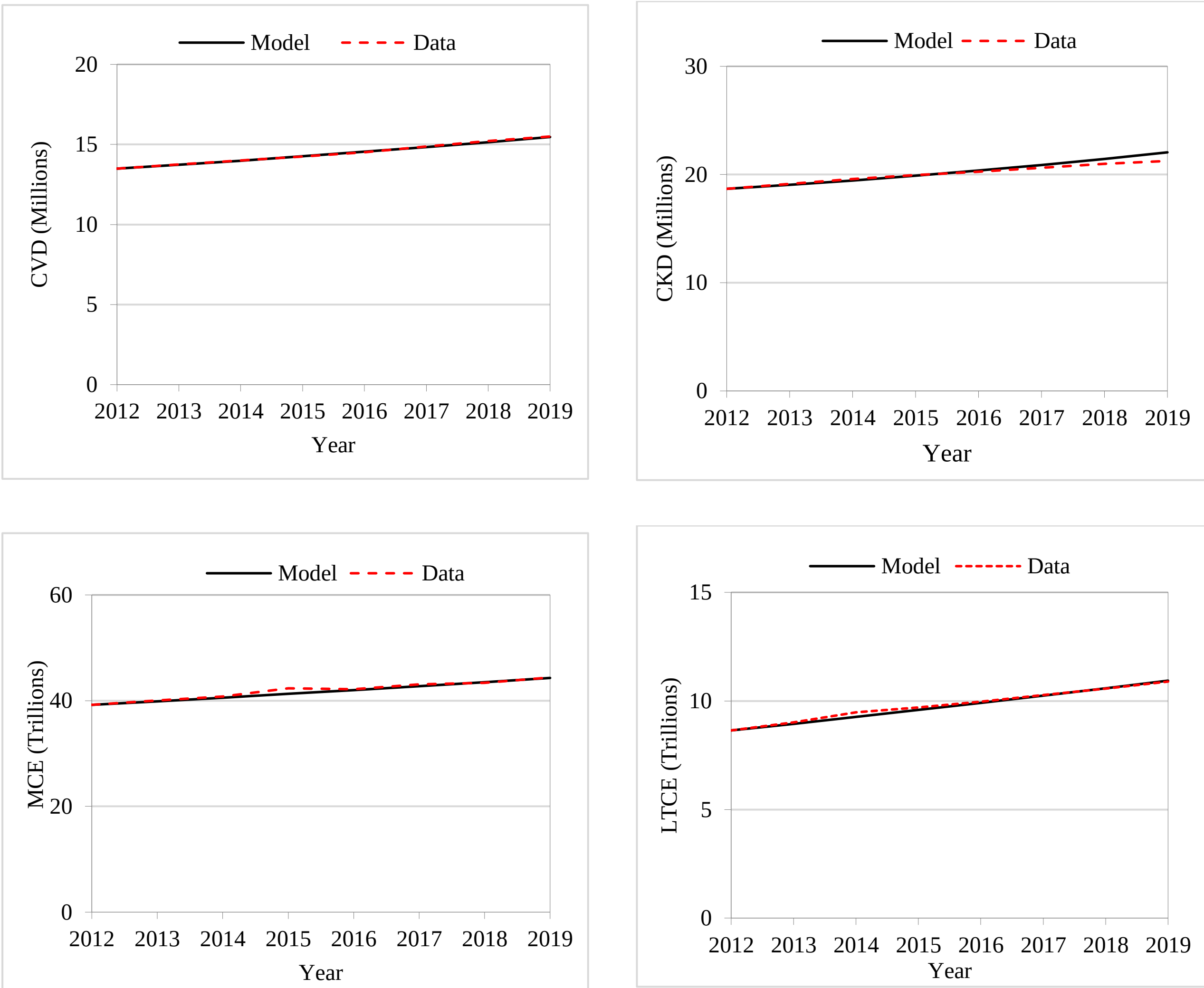

Figure 8. Behavioural reproduction test for key variables

Lastly, once we have enough confidence in the model structure's validity, the model was ready to perform certain tests to determine how accurately the model will mimic the major behavior patterns demonstrated by the real system. In the context of our investigation, the behavioral reproduction test involves comparing the simulated behavior of key variables such as CVD, CKD, medical expenditure, and long-term care expenditure with available data, as depicted in Figure 8. The output results indicate that the model behavior closely aligns with the historical data. We also assessed the validity of our simulation model by examining several key variables using four distinct metrics: coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE), and Theil inequality statistics. These metrics provide insights into the accuracy of our simulated model and the degree to which it deviates from actual data. The Theil inequality statistics particularly decompose the variance between the model and the data into three components: bias between the means of the model and the actual data (U^M), the difference in variation between the model and the actual data (U^S), and the unequal covariation between the model and the actual data (U^C) [55].

Table 2 presents a summary of statistical error measurements for the four key variables considered in the model. The results indicate that the R^2 values for all four variables are relatively high, with the fitting value of the simulated model exceeding 90%. Moreover, the majority of the MAE, RMSE, and inequality coefficient values for all four variables are reasonably low. The MAE values for the key variables range from 0.03 to 0.3, suggesting that the model values closely align with the actual values. Similarly, the RMSE values between 0.04 and 0.4 indicate a relatively accurate prediction of the data by the model. From the Theil statistics results, it is observed that most of the errors are small and unrelated to bias or unequal variance between the simulated and actual data, with U^M, and U^s values are close to 0, while U^c values are close to 1. Hence, it is reasonable to conclude that the model is capable of reproducing the behavior of real system reasonably well.

Table 2. Summary statistics of behavior reproduction

Variable	**R^2 (%)**	**MAE**	**RMSE**	**Theil Inequality Statistics**		
				U^M	**U^S**	**U^C**
CVD	99.84	0.027	0.035	0.197	0.235	0.568
CKD	97.71	0.241	0.347	0.220	0.602	0.178
MCE	95.76	0.263	0.414	0.306	0.002	0.692
LTCE	99.15	0.068	0.093	0.330	0.135	0.536

Scenario Analysis

This research conducted four scenarios, encompassing three scenarios focused on initiatives to reduce salt intake, in addition the base case. Our scenario analysis aligns two out of the three main pillars outlined in the WHO's classification of national-level salt reduction interventions such as consumer behavior and product reformulation, as well as environmental changes [56]. Food product reformulation is advocated as an effective approach to lowering population salt intake and addressing the burden of chronic diseases [57]. It is also a key component of Japan's salt reduction initiatives [17, 58]. The suggested scenario analysis allows policymakers and public health officials to assess the potential impacts of these strategies targeting the promotion of a low-salt diet behavior among Japanese population and reformulation of food, thus identifying the most effective measures.

Base-case: The baseline experiment assumes that key variables affected by policy changes, including the percentage of food reformulation related to salt content products (3%) and population's low-salt diets adoption fraction (4%) stay the same over the simulation period. This serves as a reference point for comparing with other scenarios.

Scenario 1: Promoting a low-salt diet can yield significant public health advantages by reducing the prevalence of associated health conditions. Therefore, it is essential to examine how changes in population behavior towards adopting a low-salt diet can impact overall salt intake. In our model, variations in the number of individuals embracing a low-salt diet not only directly affect salt consumption but also influence the availability of low-salt food products due to changes in demand. These changes are driven by individuals adopting a low-salt food products, which is linked to scenarios 2 and 3. Moreover, these adopters are influenced by the population's awareness of salt reduction efforts, a key component of the country's public health campaign. In our analysis, we investigated the scenario by adjusting the likelihood of the population adopting low-salt diet from 4% to 10%.

Scenario 2: Scenario 2, referred to as implementation of voluntary food reformulation policy. In this analysis, we followed previous studies [49, 59] to define voluntary reformulation by setting the estimated value of food reformulation intervention from 3% to 15%.

Scenario 3: This scenario, defines as mandatory food reformulation, involves changing the estimated value of product reformulation intervention from 3% to 20%. For this analysis, we also relied on prior research [49, 59] to adjust the degree of salt content product reformulation implemented by food companies.

RESULTS AND DISCUSSION

Baseline behavior of salt intake reduction intervention

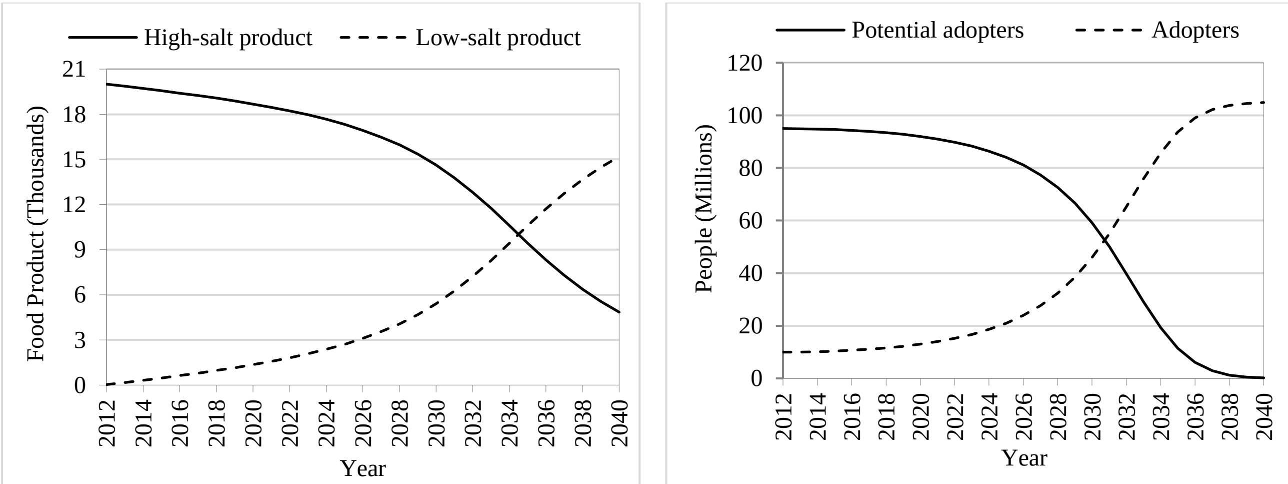

Figure 9. Baseline behavior of food reformulation and low-salt diets adoption interventions

The results depicted in Figure 9 illustrate two general patterns of S-shaped growth, one for low-salt product reformulation and another for the adoption of a low-salt diet. On the left-side of the figure depicts the behavior of high-salt and low-salt products. The food product system displays S-shaped behavior when the number of low-salt products being reformulated is low at first. Year after year, the number of low-salt products increases exponentially caused by a large initial number of high-salt products, which drives the rate at which companies reformulate their products in response to government initiatives and demand from low-salt product adopters. However, as the number of low-salt products increases, the system transitions to negative feedback loop dominance, such as when the fixed market size of the products restricts the growth of low-salt products.

On the right-side of the figure, on the other hand, as the number of potential adopters decreases, the number of adopters who learn about the low-salt diet through interactions between adopters and non-adopters increases. During the initial phase, as the curve of adopters rises and intersects with the curve of potential adopters, the number of adopters increases. Concurrently, the variables representing adoption rates also increase, reaching a peak in 2031 when the numbers of potential adopters and adopters become equal. After this point, the growth of the adopters' curve slows down because, post-2031, the values of potential adopters are lower than those of the adopter variables, resulting in fewer potential adopters transitioning to adopters. In general, the stocks of potential adopters gradually decline until they are depleted entirely or the entire population embraces low-salt dietary behavior.

Scenario Analyses

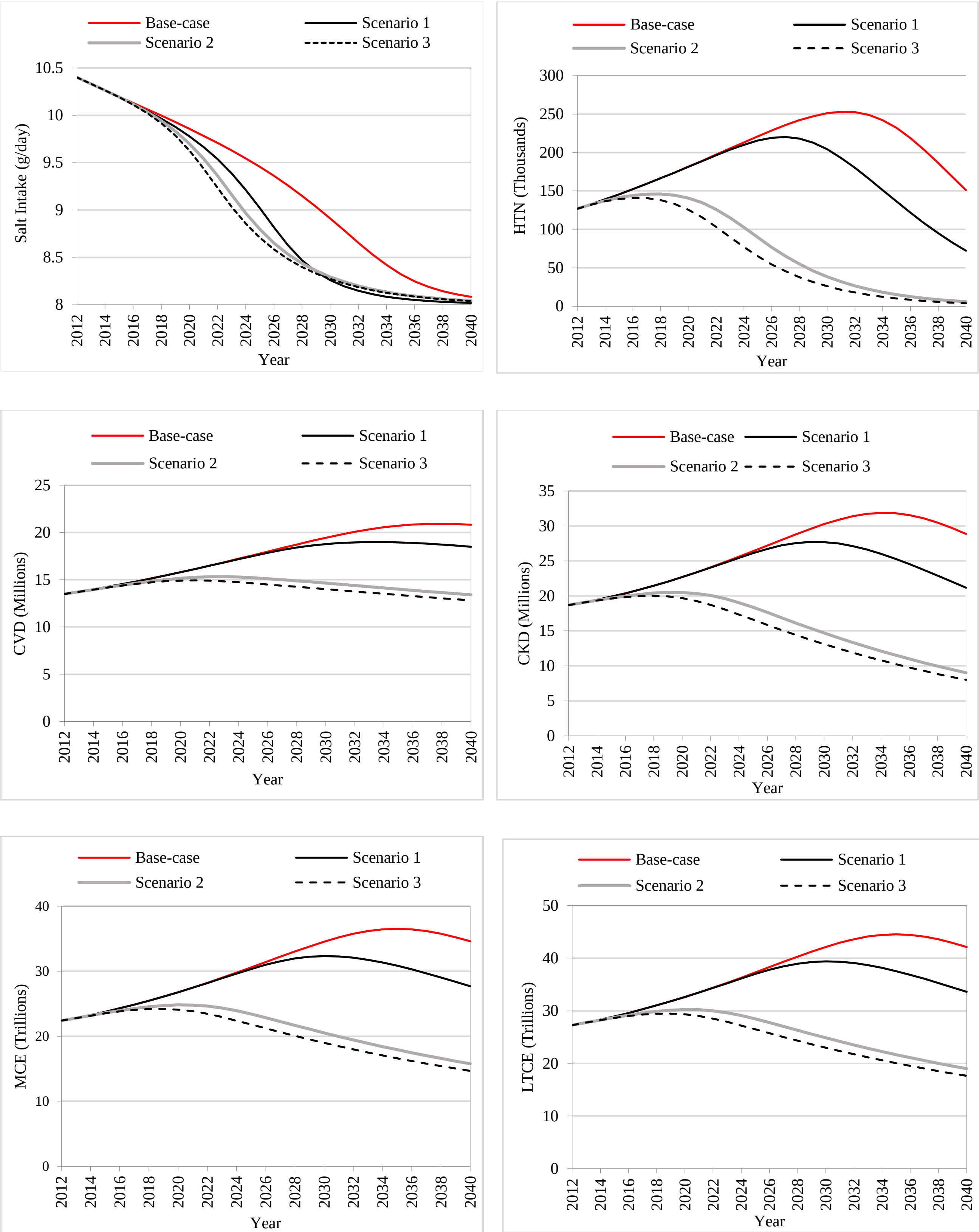

Figure 10. Behavior over-time graphs of major outcomes

Figure 10 illustrates the results of behavior over time for the experimented scenario analyses of the main outcomes pertaining to the hypothetical situation before and after the implementation of salt intake reduction interventions, as discussed in the preceding section. Under the base-case scenario, the average dietary salt intake is projected to decrease gradually, approaching the target of 8 grams by 2040 from its initial value of 10.4 grams in 2012. This decline in salt intake is attributed to the implementation of interventions such as food reformulation and the widespread adoption of low-salt diets among the population. Consequently, the figure illustrates a reduction in the prevalence of salt-related diseases, accompanied by a downward trend in the associated costs. Our findings show that if all three measures are implemented, the salt target established by Health Japan's 21 program [7] will be fulfilled, but not the WHO Global Action Plan's 30% sodium intake reduction. To achieve the goal of reducing salt intake, a more comprehensive strategy conguent with the WHO SHAKE technical package [60], is needed to advance the goal of sodium intake reduction.

The results of scenario analyses for salt intake reduction interventions can be observed from graph lines indicated as scenario 1 to scenario 3. According to the results of this scenario analysis, all of these interventions, both mandatory and voluntary food reformulation, as well as the population adopting a low-salt diet, significantly contribute to reducing salt intake, chronic diseases, and social security expenditures. This is evident in the behaviors of these scenarios, indicating lower outcomes compared to the baseline behavior represented by the red line. In the base-case scenario, by the year 2040, the cumulative populations affected by CVD and CKD would amount to around 21 million people and 29 million people, respectively, incurring total medical expenditures of 35 trillion yen and long-term care expenditures of 42 trillion yen.

In contrast, by 2040, with the implementation of promoting salt reduction intervention via increasing the number of people adopting a low-salt diet as indicated in scenario 1, the cumulative populations affected by CVD would amount to around 18 million people, and 21 million people for CKD, respectively, resulting in medical care costs of 28 trillion yen and long-term care costs of 34 trillion yen. By implementing voluntary food reformulation as indicated in scenario 2, the cumulative populations affected by CVD would amount to around 13 million people, and 9 million people for CKD, respectively, resulting in medical care costs of 16 trillion yen and long-term care costs of 19 trillion yen. By conducting aggressive salt intake reduction interventions via mandatory food reformulation, as indicated in scenario 3, the number of CVD and CKD populations could be aggressively reduced by 2040, to 13 million people, and 8 million people, covering medical care costs and long-term care costs of approximately 15 trillion yen and 18 trillion yen, respectively.

Therefore, the impact of mandatory reformulation strategy surpasses that of voluntary reformulation and the proportion of the population adopting a low-salt diet strategy. This discrepancy may arise because when mandatory food reformulation is mandated by the government, more food companies are compelled to reformulate their high-salt content products into low-salt alternatives. Consequently, with a greater availability of low-salt food options in the market, more Japanese individuals can adopt low-salt dietary habits at an accelerated rate, leading to improvements in population-wide salt intake, disease prevalence, and associated social costs. Therefore, by comparing both population initiatives and food companies' initiatives toward reducing salt intake, intervention from food companies would contribute a greater impact on the health and social costs of the country. Our findings align with previous research conducted in Japan, which suggests that mandatory or voluntary reformulation may be more preferable than other salt reduction policies in the country [59].

CONCLUSION

This study employed a system dynamics modeling approach to collaboratively address the persistent issue of high salt consumption, the prevalence of preventable chronic diseases linked to salt intake, and associated social security costs, specifically medical care and long-term care costs in Japan on a national scale. Our simulation spans from 2012 to 2040, providing a comprehensive timeframe to observe long-term effects. The research explores three types of policy experiments aimed at reducing salt intake, namely increasing the adoption of low-salt diets among the population, voluntary food reformulation, and mandatory food reformulation. The findings indicate that all these interventions negatively impact salt intake, disease prevalence, and social security costs. Encouraging the public to adopt low-salt diets and motivating the food industry to reformulate their products are mutually beneficial. The research highlights that mandatory food reformulation is the most effective approach to accelerate salt intake reduction among the Japanese population and achieve greater public health benefits. Furthermore, the study emphasizes the crucial role of the food industry in promoting low-salt diets by encouraging the population to select low-salt food products, thereby incentivizing increased production of low-salt products. The developed simulation model serves as an educational tool for government stakeholders, facilitating a thorough understanding of the interdependencies among relevant components of the system and the resulting behavioral patterns of key variables, such as average dietary salt intake, chronic disease prevalence, medical care costs, and long-term care costs.

Our study has several limitations that should be acknowledged for future research insights, particularly in simulation and other modeling studies. Firstly, there is likely variability in salt intake habits, and health status among different age and gender groups, which our study did not consider. For example, in 2012, Japanese men consumed an average of 11.3 grams per day of salt compared to 9.6 grams per day among women [34]. Furthermore, our study did not differentiate between processed and seasoning products for a variable of low-salt products used in the model. Future research should address this by considering food categories that are high (or low) in salt and commonly consumed in Japan. Overlooking these categories could lead to an incomplete understanding of dietary changes and their health impacts. Our study also acknowledges the challenges faced by food manufacturers in developing and producing low-salt products. These challenges include delays in research and development (R&D) necessary for product reformulation and the need for taste testing to ensure consumer acceptance. Such delays may slow down the market introduction of low-salt products, thereby limiting the availability of healthier food options for consumers and potentially affecting the overall effectiveness of the salt reduction strategies. Future studies should delve deeper into ways to speed up R&D for low-salt products and investigate consumer perceptions and preferences regarding taste, which are crucial for successful adoption of low-salt dietary choices. Lastly, our study did not perform a detailed cost-benefit analysis of the salt intake reduction intervention, including factors such as interventions costs, productivity gains, quality of life and other factors. Future research should consider to conduct a thorough cost-benefit evaluation to provide policymakers with clearer insights into the advantages of implementing these salt reduction strategies. By providing detailed health economic evaluations, such research can help justify investments in these interventions and highlight their long-term advantages for public health.

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