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Evaluating the health and economic impact of population-based diet policies in Germany: Development, application, and comparison of simulation modeling methods

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"They were scientists enough to admit that they were wrong."
- Isaac Asimov, Foundation

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Preface

Health is a fundamental human right and every person should have the means to exercise it. This ideal signifies that everyone, irrespective of their personal background, life circumstances, and cultural implications should have the opportunity to grow up, live, and work in an environment that enables to live a healthy life. Health itself is a complex concept and scientific disciplines, from medicine, psychology, and economics to sociology, lay emphasis on different aspects related to what health entails, how it is determined, and through which processes it is gained, maintained, and lost. Inherent to these explanatory perspectives is some conceptual understanding of the contribution of intra-individual, inter-individual, and structural (extra-individual) factors to these processes.

While many inherently individual factors, such as genetics and psychological traits, have an indisputable direct effect on individual health, many determinants are beyond the control of the individual. This becomes particularly apparent if social and political determinants are considered. One very important health determinant is itself determined by, intra-, inter-, and extra-individual forces: Human behavior. Behavior is rooted in the individual but affected by interactions with other – familiar and unknown – members of society through personal relationships and social norms and limited or enabled by – national and global – institutions and organizations. Behavioral health determinants such as unhealthy diets, physical activity, and smoking are closely related to structural aspects of society through various pathways and often follow a clear social gradient. Almost all unhealthy behaviors are more prevalent among the poor and the less educated.

In Europe, a large proportion of the health burden is related to these behavioral determinants. Particularly unhealthy diets, characterized by processed foods high in sugar, salt, and fat, play a unique role in the epidemic of obesity and the etiology of various disease, such as type 2 diabetes, coronary heart disease, and cancer. Because the availability, accessibility, and affordability of food is largely determined by the (global) food system, national (health) policy, and local food environments, which are beyond direct individual control, I believe that meaningful progress to tackle unhealthy diets can only be achieved through an interdisciplinary population health lens. This means that an emphasis on the individual responsibility to make healthy food choices is only fruitful if the structural factors that shape individual dietary behaviour are acknowledged. It is therefore among the tasks of the population health sciences to assess the impact of these structural forces on unhealthy diets (and health more general) and to show which measures to address these forces and the resulting health inequalities might (not) be beneficial.

With this dissertation I hope to contribute to an understanding of the benefits of addressing structural determinants of unhealthy diets in Europe and Germany in particular. I do so by making the potential value of policies visible in a country that historically has had an ambivalent relationship with the discipline of public health and concerns with defining (ab)normality in health in the aftermath of fascism in Germany. Therefore, perhaps, the broader goal of this work is to improve our national understanding of how public health research and policy can indeed contribute to improving population health and reducing ubiquitous health inequalities.

Karl M. F. Emmert-Fees, München, 13.05.2024

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Contents

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List of Abbreviations

ACE-Obesity	Assessing Cost-Effectiveness in Obesity
ACE-Prevention	Assessing Cost-Effectiveness in Prevention
AIDS	Almost Ideal Demand System
BAPC	Bayesian Age Period Cohort
BMI	Body mass index
BODE^3	Burden of Disease Epidemiology, Equity and Cost-Effectiveness
CHD	Coronary heart disease
CHEERS	Consolidated Health Economic Evaluation Reporting Standards
CHOICES	Cost Effectiveness of Childhood Obesity Interventions
CKD	Chronic kidney disease
COPD	Chronic obstructive pulmonary disease
cPE	Cross-price elasticity
CRA	Comparative risk assessment
CVD	Cardiovascular disease
DALY	Disability-adjusted life year
DiD	Difference-in-differences
EBM	Energy balance model
EGDRC	Emory Global Diabetes Research Center
EU	European Union
EUPHA	European Public Health Association
Food-PRICE	Food Policy Review and Intervention Cost-Effectiveness
g	Grams
GBD	Global Burden of Disease
GDP	Gross domestic product
GLP-1	Glucagon-like peptide-1
HFSS	High in Fat, Salt, and Sugar
HIC	High-income country
HIV	Human immunodeficiency virus
HLE	Healthy life expectancy
HRQoL	Health-related quality of life
HTA	Health Technology Assessment
ICS	Income and Consumption Survey
IF	Impact Factor
IGM	Institute for Health Economics and Healthcare Management
INDEPENDENT	Integrating Depression and Diabetes Treatment
ISPOR	International Society for Pharmacoeconomics and Outcomes Research
IV	Instrumental variable
JPI HDHL	Joint Programming Initiative on a Healthy Diet for a Healthy Life
KORA	*Kooperative Gesundheitsforschung in der Region Augsburg*
l	Liters
LMIC	Low- and middle-income country
LMU	The Ludwig-Maximilian University of Munich
MASE	Mean absolute scaled error
ml	Milliliters

(Continued)

MSLT	Proportional multi-state life table Markov cohort
NCD	Non-communicable disease
NDNS	National Diet and Nutrition Survey
NHANES	National Health and Nutrition Examination Survey
NICE	National Institute for Health and Care Excellence
NIH	The National Institutes of Health
NVS II	*Nationale Verzehrsstudie II*
OECD	Organisation for Economic Co-operation and Development
oPE	Own-price elasticity
OSF	Open Science Framework
PEN	Policy Evaluation Network
PHP	Professorship of Public Health and Prevention
POHEM	Population Health Model
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QALY	Quality-adjusted life year
RDD	Regression discontinuity designs
RIGOR	RIGorous inference in Obesity Research
SDG	Sustainable Development Goals
SDIL	Soft Drinks Industry Levy
SHI	Statutory health insurance
SMR	Standardized mortality ratio
SSB	Sugar-sweetened beverage
T2DM	Type 2 diabetes mellitus
TAC	Thesis advisory committee
TFA	Trans-fatty acid
TUM	The Technical University of Munich
UK	United Kingdom
UKPDS	United Kingdom Prospective Diabetes Study
UPF	Ultra-processed food
US	United States
WCRF	World Cancer Research Fund
WHO	World Health Organization
WP	Work Package
YLD	Years lived with disability
YLL	Years of life lost

Part I.

Introductory summary

1. Background

1.1. The predominance and societal burden of non-communicable diseases in the 21st century

1.1.1. The global health burden of non-communicable diseases

Non-communicable diseases (NCDs) pose a tremendous threat to global human health and societies in the 21st century because they are the leading cause of chronic disabling morbidity and premature mortality [1–4]. This is also reflected in the United Nations Sustainable Development Goals (SDG) target 3.4, which states that premature mortality from NCDs should be reduced by one third in 2030 compared with 2015 [3, 5]. In 2021, 82% of the global years lived with disability (YLD) and 56% of the global years of life lost (YLL), excluding COVID-19[1], resulted from NCDs [4]. The leading causes of the global burden of NCDs in terms of disability-adjusted life years (DALYs), a measure that combines impacts of diseases on both YLD and YLL, are cardiometabolic diseases and cancer. In 2021, cardiovascular disease (CVD) accounted for 25% of NCD-related DALYs, diabetes and kidney disease for 7%, and cancer for 15%. Other NCDs, such as mental disorders and respiratory diseases, were responsible for a further 15% [4]. In the high-income countries (HICs) of North America and Europe, this contribution of NCDs is even larger, although it has to be considered that the majority of global deaths from CVD and cancer as well as 80% of type 2 diabetes mellitus (T2DM) cases occur in low- and middle-income countries (LMICs) [6–8].

Beyond their relative importance for the global mortality and morbidity burden, cardiometabolic disease and cancer have a very high absolute burden, particularly in older age groups, affecting the health and health-related quality of life (HRQoL) of millions of people globally [6, 9]. The global prevalence of CVD was around 523 million cases in 2019, of which around 197 million were due to coronary heart disease (CHD) and 101 million non-fatal strokes [9]. According to recent estimates, there were 10.1 million incident cancer cases among men in 2020, of which lung (14.3%), prostate (14.1%), and colorectal cancer (10.6%) were the most common. For women, breast, colorectal, and lung cancer accounted for 24.5%, 9.4%, and 8.4% of the 9.2 million incident cases respectively [6]. T2DM plays a particularly important role in the global burden of NCDs because it is a key risk factor for CVD, increases the risk for some cancer types, and is itself a slowly progressing chronic disease with a high morbidity burden that causes irreversible organ damage if uncontrolled [10, 11]. The global prevalence of T2DM in 2021 was 6.1%, thus affecting over 500 million people, of whom around 50% experience microvascular complications, such as retinopathy, neuropathy, chronic kidney disease (CKD), diabetic foot, and even lower extremity amputations, and 27% are affected by macrovascular complications such as CVD [8, 11, 12].

Importantly, projections indicate that the absolute global burden of CVD, cancer, and T2DM, especially in LMIC, is likely to increase further if current incidence trends continue and as the global population keeps increasing in size and continues to age [6, 8, 9, 13–16]. According to recent estimates, the global prevalence of T2DM might reach close to 10% in 2050, equating to more than 1.3 billion individuals living with the disease [8]. Similarly, the global burden of cancer is also projected to increase by almost 50% in 2040 compared with 2020 [6]. The unfolding climate crisis also has profound implications for health, such as cardiovascular stress resulting from the increased likelihood and severity of heat waves [17–19].

[1]When including the health burden of COVID-19, the numbers are very similar, and 81% of the global YLD and 50% of the global YLL burden were due to NCDs.

1.1.2. Economic impacts of non-communicable diseases

In addition to impacts on human health and well-being, the morbidity and premature mortality related to NCDs pose tremendous challenges for the global economy and social care systems through direct and indirect economic costs [20–24]. Within the healthcare sector, the diagnosis, treatment, and management of NCDs requires extensive resources in terms of medical devices, medication, and personnel costs for health care professionals [22, 24, 25]. If diagnosed, NCDs typically require constant medical attention to avoid disease progression and potentially fatal complications [26]. For example, depending on the country context, patients with T2DM have around twice the healthcare costs as those without the disease [27–29]. Additionally, novel therapeutics, such as glucagon-like peptide-1 (GLP-1) receptor antagonists to treat T2DM and targeted molecular cancer treatments, are be very expensive [30, 31]. In the wider societal context, NCDs additionally lead to increased rates of absenteeism (i.e., not being able to work due to illness), presenteeism (i.e., being less productive at work due to illness), early retirement and premature mortality, which all decrease economic productivity [22–24, 32]. The high care burden of many NCDs also affects patients regarding time costs for self-management and healthcare utilization. Additionally, the productivity of patients' family members, particularly women, is often also reduced through informal care arrangements [24, 25, 32].

The global costs of diabetes in 2015 have been estimated at around US$1.3 trillion, which is equivalent to almost 2% of the global gross domestic product (GDP). Productivity losses account for about 35% of these costs [32]. Similarly, the global macroeconomic burden of cancer from 2020 to 2050 will be around $25 trillion (in 2017 international dollars), particularly attributable to lung, colorectal, and breast cancer [23]. In the European Union (EU), the economic burden of CVD, cancer, and respiratory diseases is around 2% of GDP and the healthcare costs of CVD alone were responsible for 11% of the EU healthcare expenditure in 2021 [21, 22]. Additionally, the costs of informal care giving related to CVD in the EU were estimated to be €80 billion, which is about 30% of the total economic burden [22]. In the United States (US), CVD care-giving costs are projected to reach US$128 billion in 2035, which is a twofold increase since 2015 [25].

1.1.3. The increasing burden of non-communicable disease morbidity

It is important to consider that the share of NCDs in the global disease burden has increased continuously over the past decades and that the respective contributions of morbidity and mortality have shifted. While in 1990, around 43% of total global DALYs were related to NCDs, this has increased to around 65% in 2021, and the overall contribution of NCDs to the global age-standardized DALY-rate has also increased from 50% to around 62% (excluding COVID-19)[2] [4]. Primarily because of changes in population size and age structure, the absolute morbidity and mortality burden from CVD and cancer has increased by up to 90% over the same period [4, 9].

However, driven by reductions in mortality rates, the global age-standardized DALY rates of CVD and several cancers have decreased continuously over decades [4, 6, 7, 9, 33]. These reductions were primarily achieved through better primary and secondary prevention, such as screening for colorectal cancer and high blood pressure, widespread prescription of cholesterol-lowering drugs, better access to acute care, such as stroke units, and new therapeutic options for cancer, which have improved outcomes and prognosis [34–37]. Thus, as global life expectancy has increased from 51.6 and 46.7 years for women and men in 1950 to 76 and 70.8 years in 2019, there has been a continuing shift from mortality toward a higher relevance of morbidity (i.e., a higher contribution of YLD) [4, 38]. Although the COVID-19 pandemic reduced global life expectancy in 2021 for women and men to 74.8 and 69 years, the trend of an increasing NCD morbidity burden continues, and recent estimates show that most countries have reverted to their pre-pandemic mortality trajectories [38–41]. Yet, in recent years, evidence is mounting that these historic declines in CVD mortality are slowing down [42, 43].

Some of the contemporary factors that shape these past and current trends in the burden of NCDs and their historic foundation are described in the following sections.

[2] Including COVID-19, 60% of the total global DALYs in 2021 were related to NCDs, and the contribution of NCDs to the global age-standardized DALY-rate in 2021 was 57%.

1.2. The historic socioeconomic foundation of non-communicable diseases

The global long-term drivers of changing disease patterns toward a predominance of NCDs were several developments since the 19th century that have been theoretically and empirically described as part of an epidemiological and demographic transition [44–47]. In Europe, through a range of societal upheavals, accompanied by technological advancements, industrialization, expansion of education, reduction in subsistence agriculture, and economic growth, mortality and fertility decreased [44–48]. While mortality from all causes and across all age groups decreased, this is especially true for infectious causes and child mortality [45, 48, 49]. In particular, medical innovations, such as vaccinations and antibiotics, higher availability and accessibility of healthcare, better hygiene, increased food security, and higher living standards, contributed to improvements in population health and life expectancy over the last centuries [47, 48]. While these changes happened first in Europe and North America, reflecting the global political and economic dominance of these regions at the time, largely as a result of colonialism, the core features of this transition and an increasing burden of NCDs have since been observed in all countries alongside economic development [44, 50, 51].

These historic civilizational developments are important for understanding the current burden of NCDs, because they were characterized by a fundamental transition that shaped the structural and lifestyle factors which play a key role in the etiology of cardiometabolic diseases and cancer today. On the one hand, the transition from pre-industrial economies without mechanization to globalized post-industrial service economies arguably benefited population health because of improvements in healthcare and reductions in undernutrition and poverty [48, 52]. On the other hand this transition also led to (1) the large-scale availability, accessibility, and affordability of industrially manufactured foods that are often highly processed [52, 53]; (2) decreases in physical activity and increases in sedentary behavior due to predominantly automotive transportation, increasing urbanization, automation of industrial production, and digitalization [54, 55]; and (3) the mass production and thus cheap availability and marketing of cigarettes and other tobacco products [56, 57].

1.3. The role of unhealthy lifestyles in the etiology of non-communicable diseases

The unhealthy lifestyle factors to which this transition gave rise are foremost smoking, unhealthy diets, physical inactivity, and to some degree alcohol consumption [58]. Besides old age, these constitute the most important determinants of NCDs and play a key role in their etiology through direct and indirect effects on cardiometabolic risk, and overweight and obesity (respectively defined as a body mass index (BMI) $\geq$25 kg/m^2 and $\geq$30 kg/m^2) [59].

Broadly, unhealthy lifestyle factors exhibit complex negative effects on the human metabolism, circulatory system, endocrine system, and genetic processes through various mechanisms and often affect the pathophysiological pathways of multiple NCDs [11, 16, 60–63]. Although these underlying mechanisms are often not fully understood, they primarily relate to oxidative stress, chronic inflammation, cell and DNA damage, irregularities in blood lipids (dyslipidemia), endothelial dysfunction, and arterial stiffness (i.e., *arterio*sclerosis) [11, 16, 60–65]. As these processes progress over time, they cause and are reinforced by clinical preconditions that manifest as chronic diseases in the long term. Important pathways include, among others, high blood pressure (hypertension) and the buildup of atherosclerotic plaques that cause CVD [63, 65, 66]; insulin resistance, which leads to high blood glucose (hyperglycemia), contributing to the development of T2DM and its micro- and macrovascular complications; and genetic mutations that lead to abnormal cell growth and potentially manifest as cancer [61, 63, 64].

However, one key aspect is that unhealthy lifestyles are themselves influenced by structural upstream factors, genetic predispositions, and the individual psychological makeup, which are largely beyond direct individual control [58, 67]. These factors interact dynamically on different levels in societies, from political institutions and cultural practices to living and working conditions, social networks, family arrangements, parenting practices, and epigenetic adaption mechanisms to environmental stressors [67]. These interactions shape human behavior, creating its individual and societal context and reproducing social stratification along socioeconomic characteristics, such as education, income, and occupation [67, 68]. As a consequence, there are substantial, persisting socioeconomic inequalities in almost all health-related outcomes to which unhealthy lifestyles contribute (i.e., social production of disease) [68–75]. How these processes work has been extensively empirically described in social epidemiological research and discussed based on theoretical work, such as the famous "Rainbow Model" of Dahlgren and Whitehead from 1991 or the framework of the 2008 World Health Organization (WHO) Commission on Social Determinants of Health [76–79].

The contribution of unhealthy lifestyle factors to the burden of NCDs is described in detail in the following sections. Hereby, a particular focus is put on unhealthy diets and obesity, which are the focus of this dissertation but, for contextual reasons, smoking and alcohol consumption are also described briefly.

1.3.1. Health effects of smoking and alcohol consumption

Following the large-scale availability of cigarettes, smoking prevalence has increased substantially in the first half of the 20th century, peaking at over 50% of the adult population in the 1950s and 60s in some countries [56, 57, 80]. Owing to carcinogenic substances created during the combustion of tobacco and the inhalation of particulate matter and toxic compounds, smoking is the main cause of lung cancer, a leading risk factor for the development of chronic obstructive pulmonary disease (COPD), and a major risk factor for CVD [81]. Around 70% of lung cancer deaths, 10% of deaths from CVD, and 5% to 13% of DALYs for women and men, respectively, are attributable to smoking [82–85]. Recently, lung cancer incidence among women has been increasing, which is largely explained by the fact that women historically adopted smoking later [59, 86, 87]. However, it has been shown that the adoption of population-based prevention policies to control tobacco use, accelerated by the WHO Framework Convention on Tobacco Control in 2005, and the subsequent reduction in smoking rates have contributed to the observed reductions in CVD mortality and lung cancer incidence, particularly among men [57, 59, 88–91].

In contrast to smoking, the minimum exposure level of alcohol is controversial, and low consumption may even provide cardiovascular benefits [92]. However, high consumption of alcohol is an important risk factor for CVD, through an increased risk for hypertension and dyslipidemia, and is associated with several cancers, such as those of the female breast, the oral cavity, the gastrointestinal tract, and, through its metabolization to acetaldehyde in the liver and associated liver cirrhosis, the liver [92–94]. Additionally, alcohol intake also increases the risk for T2DM [93]. Around 4% of all incident cancer cases are attributable to alcohol [95]. Of female and male DALYs 1% and 6% are related to alcohol use and around 50% of alcohol-related DALYs are caused by CVD [84, 92]. Additionally, alcohol consumption poses the risk of addiction, is responsible for interpersonal violence, and is the main cause of premature death for men in younger age groups due to increased risk for injuries [92, 93, 96]. Evidence shows that the mortality crisis in Russia in the early 1990s was partially related to increases in the affordability and excessive consumption of alcohol during the economic transition to a market economy and the dissolution of the Soviet Union [97, 98].

1.3.2. The nutrition transition and the importance of unhealthy diets

Determinants of food intake and the role of the nutrition transition

Unhealthy diets are arguably the most important and complex lifestyle risk factor in the etiology of NCDs. Dietary components provide energy and are needed to sustain normal human physical and mental functioning, but may also exhibit specific negative metabolic and carcinogenic health effects at higher intake levels [52]. In addition, food intake is determined by various individual, interpersonal, environmental, and political-economic factors [99–102]. Individuals may, for example, have different oral sensory perception, eating regulation, and food-related knowledge, skills, beliefs, and habits. Within families and communities, diets are further shaped, among others, by parental attitudes and beliefs, socioeconomic household characteristics, social norms, and cultural practices. These individual and interpersonal factors interact with food environments that determine the availability and accessibility of different foods through natural geographic aspects and outlet density. Local environments further influence the affordability of particular diet patterns through food prices, exposure to promotions, and portion size. Finally, on a macro-level, diets are also shaped by the political economy of the global food system, such as the goals and opportunities of food industry actors (i.e., commercial determinants of health), related governmental regulation, agricultural policies, and international trade agreements [99–103].

The dichotomy between the fundamental necessity of nutrition and the negative effects of some dietary components is also reflected in the nutrition transition that has continued to shape the global diet-related health burden over the past decades [52, 104]. Historically, the importance of diets for human health was primarily related to undernutrition and food insecurity [52, 53]. As societies transitioned to (post-)industrial market economies and agricultural technology advanced, famines and malnutrition receded through an increase in the global food supply. However, at the same time, food consumption and energy expenditure patterns changed through decreases in physical activity associated with urbanization and profound changes in the global food system and local food environments, which increased the availability, accessibility, and affordability of industrially produced, often ultra-processed foods (UPFs), to which humans are evolutionary maladapted [52, 104, 105].

Complexity in assessing the healthiness of diets

To understand the impacts of these developments on human health, it is paramount to assess and understand the complex relationship between nutrition and health. In general, the healthiness of diets can be analyzed from different perspectives, including micronutrients (e.g., minerals, vitamins), macronutrients (e.g., protein, carbohydrates), food groups (e.g., meat, grains), dietary patterns (e.g., Mediterranean diet, vegetarian diet), and total calories [53, 106]. Additionally, foods may be subject to different levels of individual or industrial processing [106, 107]. Recent studies further point out that the combination of dietary components in a meal may have specific health effects beyond their individual contributions [106, 108].

This complexity makes it particularly challenging to disentangle the causal health effects of certain dietary components in typical observational epidemiological studies [109–111]. Such analyses are additionally complicated by correlations between diet components and measurement biases as food intake is almost impossible to measure directly and thus often based on self-report at the expense of validity and reliability [110, 112, 113]. The resulting estimates may thus not be truly causal and suffer from biases such as residual confounding and regression dilution [110, 111, 113].

According to current understanding of the relevance of unhealthy diets in the etiology of NCDs, several aspects need to be considered and are discussed throughout the next sections: (1) the effects of specific dietary components that affect health or metabolic mediators (e.g., systolic blood pressure, serum cholesterol, fasting plasma glucose) directly [109, 114]; (2) the health effects of food processing [104, 107, 115]; (3) and health effects mediated through BMI (i.e., overweight and obesity) [52, 116, 117].

Dietary risks independent of body mass index

Multiple dietary risk factors have been identified over the past decades, which in 2017 accounted for 22% of deaths and 15% of DALYs resulting from CVD, cancer, and T2DM, independent of BMI [109, 118]. Foods and dietary components that are beneficial for health, but are often not consumed in high enough quantities include fruit and vegetables, whole grains, legumes, nuts and seeds, seafood, fiber, and polyunsaturated fatty acids [106, 109, 114]. On the other hand, red and processed meat, added sugar, particularly from sugar-sweetened beverages (SSBs), sodium, highly refined grains, and trans fatty acids have specific negative effects on human health above certain thresholds [106, 109, 114, 119, 120]. For example, a high intake of sodium is among the most important dietary risks, and intake levels above 2-3 grams (g) per day are not recommended because of the established dose-response relationship with systolic blood pressure and thus hypertension, which is a key risk factor for CVD [109, 120]. In contrast, fruits, vegetables, and whole grains have been repeatedly shown to have protective cardiometabolic and anticarcinogenic effects due to their anti-inflammatory properties as well as high fiber and antioxidant content [106, 108, 109].

Because diets are largely impacted by cultural and natural geographic factors, the relevance of different dietary risks varies sometimes substantially between regions. For example, the intake of processed meat and added sugars from SSBs plays a far higher role in the HIC of Europe and North America than in Sub-Saharan Africa and Asia [109]. Dietary guidelines, such as the "Dietary Guidelines for Americans" or the "10 guidelines for a wholesome diet" of the German Nutrition Society, use the existing evidence to provide recommendations taking this national context into account [121].

Health effects of ultra-processed foods

As part of the global nutrition transition, new industrial food technologies have led to an unprecedented rise in the availability of UPFs [52, 104]. While the processing of food has been part of all cultures since ancient times, UPFs are defined as foods produced with a variety of industrial food processing techniques such as cooking, deep frying, pickling, extrusion, and fat hydrogenation, regularly including the addition of salt, sugar, fats, preservatives, and aroma compounds to produce specific taste profiles and make products more durable [107, 115]. Typically, UPFs are characterized by a high energy density and are often High in Fat, Salt, and Sugar (HFSS) with an unfavorable nutrient profile [104, 107]. Energy intake from UPFs in HICs has increased substantially over the past decades and now constitutes more than 50% of energy intake in some countries. In recent years, increases in the consumption of UPFs have also be observed in many LMICs [52, 104, 115, 122–124].

Evidence on the detrimental health effects of UPFs is emerging and has gained increasing attention in recent years [52, 104, 107]. High consumption of UPFs was found to be associated with hypertension, dyslipidemia, inflammatory bowel diseases, T2DM, CVD, obesity, and all-cause mortality in observational cohort studies [115, 124–127]. In particluar, red processed meat and SSBs may be related to a higher health risk, including multimorbidity [128–133]. However, there is also direct experimental evidence that diets consisting of UPFs lead to increased calorie intake and weight gain compared with nutrient-matched diets of unprocessed foods, which may be partially related to satiety and oral processing [134, 135].

Through these mechanisms and due to their ubiquitous accessibility, UPFs also likely play a major role in the epidemic of obesity [52, 136].

1.3.3. Unhealthy diets and obesity

The obesity epidemic

Connected to unhealthy diets and the nutrition transition, overweight and obesity have emerged as a leading risk factor for NCDs over recent decades [50, 52, 116, 117, 137, 138]. Since 1990, the prevalence of adult obesity has roughly doubled for women and tripled for men, albeit with complex national trajectories [138]. According to recent estimates, the global prevalence of obesity was around 19% for women and 14% for men in 2022 with an additional substantial proportion of the population being overweight [138]. In the US, almost every second adult is obese and 3 in 4 are overweight [139]. In Europe, 16% of adults are obese and around 50% are overweight [140]. Especially in emerging economies such as India and China, the prevalence of obesity has roughly increased 10-fold since 1990 [138, 141, 142]. There has also been a substantial increase in the proportion of overweight or obese children in many countries [138]. Crucially, projections indicate that the global prevalence of obesity is still likely to rise substantially in the future [141–144].

The health effects and burden of obesity

Obesity is a complex condition with manifold negative health consequences, the risk of which increases alongside BMI [117, 145]. To account for this increasing risk and provide adequate treatment, different classes of severity have been established (Class I: BMI 30-34.9 kg/m^2; Class II: BMI 35-39.9 kg/m^2; Class III BMI $\geq$40 kg/m^2)[3] [148]. The increased accumulation of body fat, especially visceral fat, associated with obesity interferes with several metabolic processes leading to chronic inflammation, hypertension, and dyslipidemia (i.e., metabolic syndrome), which are important risk factors for CVD [63, 117, 149]. Obesity is also the most important risk factor for the development of T2DM as it triggers the cycle of insulin resistance of body tissues and impaired insulin secretion as a result of depletion of pancreatic β-cells, which leads to increased levels of blood sugar (i.e., hyperglycemia) [11, 64, 150]. Beyond these pathways, obesity also increases the risk for several cancers, respiratory diseases, and musculoskeletal disorders [116, 151–153]. Obesity further negatively affects the risk for mortality in the general population[4] [155].

As a consequence, the contribution of overweight and obesity to the global burden of disease has increased by about 50% since 1990. In 2017, 22% of global DALYs related to CVD were attributable to a high BMI [116]. Overweight and obesity also contributed significantly to the DALY burden of other NCDs such as diabetes and kidney disease (38%), liver cancer (19%), esophageal (12%) and colorectal cancer (9%) [116]. Through these impacts, overweight and obesity also incur a substantial economic burden, which was estimated at around 2% of global GDP in 2019 [156–158]. If recent prevalence trends continue, economic impacts might roughly quadruple in HICs and increase more than 12-fold in LMICs by 2060 [156].

Explanatory perspectives on the rise of obesity

The explanation for the sustained global rise in obesity rates is still subject to some debate and proposed to be multifactorial [105, 159, 160]. Individual genetic predisposition is important in the etiology of weight gain and might explain up to 80% of body weight variability [105, 161]. However, this cannot explain the observed sharp increase in obesity prevalence over a short time frame despite hypothesized biological and epigenetic adaption mechanisms triggered by long-term exposure to UPFs [105, 159]. Rather, the prevailing theoretical model, the energy balance model (EBM) of obesity, suggests that obesity is primarily the result of a long-term imbalance in energy intake and expenditure [105, 162–164]. According to the EBM, this imbalance is a result of increased food intake caused by a complex interplay of external triggers from the food environment that affect brain activity, for example in terms of food reward and sensory processing, endocrine mechanisms and metabolic processes [105, 134]. Importantly, inter-individual genetically determined variability, particularly in the cerebral processes involved, leads to a differential propensity to develop obesity in certain food environments [105].

The rise in obesity rates in the US and other HICs since the 1970s is thus primarily explained by a sharp increase in refined carbohydrates and fats in the food supply, which have acted together with reductions in energy expenditure through urbanization [52, 105, 117, 165]. One critique of the EBM is that self-reported energy intake in national surveys, for example in the US National Health and Nutrition Examination Survey (NHANES) and the United Kingdom (UK) National Diet and Nutrition Survey (NDNS), has even marginally decreased over time while obesity rates have increased [159]. However, this discrepancy is likely explained by differential underreporting of energy intake according to obesity status [160].

In light of these observations, particularly SSBs, which are a UPF that is not unanimously defined but usually operationalized as beverages that contain "caloric sweeteners such as sucrose, high-fructose corn syrup (HFCS) or fruit juice concentrates among others, which are added to the beverages by manufacturers, establishments or individuals" [149] (p. 206, Box 1), are often identified as a crucial contributor to obesity [106, 149]. The primary reason, beyond their widespread availability and easy affordability, is their typically high calorie content due to free sugars and the fact that liquid calories do not lead to a similar satiety response as those consumed from solid foods, thus negatively affecting

[3] Although BMI itself is an imperfect measure of obesity compared with the waist-to-hip ratio or body fat percentage, it is often used because of its simplicity and ease of application in large studies [146, 147].

[4] For an overview of the paradoxical beneficial effect of obesity on mortality among subpopulations with pre-existing conditions, see [145] and [154].

energy balance [149, 166]. This is also supported by experimental evidence [167]. Additionally, SSBs might have further direct negative cardiometabolic effects, for example due to glycemic spikes [149].

Acknowledging the described cardiometabolic risks associated with obesity, these developments further suggest the conjecture that the epidemics of obesity and T2DM, together with diminishing returns of existing prevention efforts addressing other key NCD risk factors (e.g., smoking), may be partially responsible for the slowing declines in CVD mortality observed over recent years [42, 43, 168].

1.4. Population-based policies to improve population diets and prevent obesity

1.4.1. Defining population-based prevention

To prevent the health risks and reduce the economic burden associated with unhealthy diets and the obesity epidemic, several population-based policy approaches have been proposed across government sectors taking the key environmental and political-economic determinants of food intake into account [101, 106]. Such approaches have been described as primordial prevention because they ideally act on NCD risk factors across whole populations over the life course of individuals even before clinical precursors such as dyslipidemia and hypertension manifest [60, 169]. Yet, primordial prevention is always closely interlinked with primary prevention, which seeks to address these risks directly and irrespective of whether they may already have developed [60, 169]. It has been shown that about 50% of previous reductions in CVD were achieved through primordial and primary prevention (also see Section 1.3.1) [168, 169]. In correspondence with Geoffrey Rose's population health paradigm, population-level preventive (diet) policies are deemed more effective and may be more cost-effective than, for example, personalized (nutrition) interventions and risk factor control in clinical settings, which nonetheless also play a role in a comprehensive approach to improving population health [106, 170–173].

1.4.2. Examples of population-based diet policies

The importance of population-based diet policies is also reflected in the "best-buy" policies recommended by WHO and the NOURISHING framework developed by the World Cancer Research Fund (WCRF), which provide a comprehensive overview of policy options to improve diets and prevent obesity [106, 174–176]. Recommended policies include, for example, (1) labels to make the overall nutritional value of food products or the content of specific micro- or macronutrients easily visible and understandable for consumers (e.g., the Nutriscore system or warning labels on sodium, saturated fat, sugar, and calories in Chile [177, 178]); (2) advertisement restrictions on HFSS foods and/or UPFs particularly to children in public or in the media, to reduce the effectiveness of marketing of unhealthy foods (e.g., restrictions on HFSS food adverts on the London public transport system and on British TV programs aimed at children [179, 180]); (3) promotion and health education campaigns, for example to increase the intake of fruit and vegetables (e.g., the Change4Life campaign in England [181]); (4) procurement standards including the implementation of national dietary guidelines in schools and public cafeterias (e.g., nutrition standards in Californian secondary schools [182]); (5) voluntary or mandatory reformulation of processed foods with regard to unhealthy aspects of their nutritional content to address supply-side determinants (e.g., the salt reduction strategy of the UK Food Standards Agency or the ban on industrial trans-fats in Denmark [183, 184]); and (6) fiscal policies that reduce the price of healthy foods through subsidies, thus increasing their affordability, and/or increase the price of unhealthy foods through taxes, thus providing financial incentives and signals to reduce their consumption (e.g., taxation of SSBs or subsidies for fruit and vegetables [185])

Owing to their likely role in the global rise in obesity, the taxation of SSBs in particular has gained much attention from policymakers and researchers alike over recent years [149, 186, 187]. Currently, over 50 jurisdictions globally have implemented a tax on SSBs [188]. Additionally, the WHO officially recommends the introduction of SSB taxation to reduce obesity and improve population diets as part of their "best-buy" policies and has recently released guidance for governments seeking to adopt such a policy [176, 189]. Preliminary evidence indeed suggests that SSB taxation increases prices and reduces purchasing of taxed beverages [186, 187]. However, observational evidence on their effectiveness with regard to health outcomes is still largely missing and is only accumulating recently[5] [189–191].

1.4.3. Important considerations regarding population-based prevention approaches

While population-based diet policy approaches are primarily distinguished with regard to their target population (e.g., children, adults, specific settings) and mechanism (e.g., price change, salience of health risk), another important dimension is their varying requirement of individual agency [192, 193]. For example, reducing the sodium content in foods through mandatory reformulation does not require the same amount of agency from consumers as an information campaign on the health risks related to excessive sodium consumption. In the latter, individuals first have to be aware of the campaign, perceive it as important, understand its meaning, evaluate its relevance, and make the decision to change their behavior, for example with regard to buying a certain unhealthy food product (with high sodium content) [193, 194]. More structural policies, such as enforcement of nutritional standards and fiscal policies, are thus often recommended because they aim to change upstream food system determinants, partially circumvent individual differences in food-related knowledge and the perceived importance of diets for health, and are thus likely to be more cost-effective and effective in reducing diet-related health inequalities [106, 172, 193].

However, structural policies also often tend to be more invasive and have more far reaching ethical implications [192]. Although subject to philosophical and political debate, the primary rationale for (potentially extensive) government intervention on unhealthy diets lies (1) in the considerable externalities in terms of healthcare costs and productivity losses that are the result of the diet-related health burden and are born by societies [22, 32, 156, 192, 195]; and (2) in the observation that dietary patterns are largely influenced by the global food system (e.g., agricultural policies, food logistics) and local food environments (e.g., food prices, the accessibility of grocery stores, healthy school meals), beyond individual factors such as taste preferences and cooking skills [106, 174]. However, the implementation of population-based diet policies is challenging as a result of the mentioned sociocultural relevance of food and often extensive industry opposition [196–198].

1.5. The evaluation of population-based diet policies

Currently, the global implementation of population-based policies proposed to address unhealthy diets and obesity is very heterogeneous, and many countries lack a comprehensive cross-sectoral approach, which is likely needed [106, 199]. Thus, evaluations of the health and economic impacts of diet policies are key to support evidence-based public health policy decisions and increase the adoption of effective prevention measures [101, 106, 174]. As a consequence, a large body of research has aimed to gather evidence from studies applying various methods to assess the (cost-)effectiveness of population-based diet policies [186, 187, 194, 200–211]. However, as new evidence is emerging, the context-specific, direct, and robust evaluation of the health and economic impacts of diet and obesity policies is an ongoing scientific task with many methodological challenges caused by the complex effects of these policies [169, 212–214].

[5] A broader discussion of the evidence on the effectiveness of SSB taxation and other policies is beyond this introduction. However, challenges in establishing this evidence are discussed in Section 1.5 and closely intertwined with the objectives of this dissertation. See also the publications in Part 2.

1.5.1. Methodological challenges in the evaluation of diet policies

As discussed, diet policies have the ultimate goal of reducing the diet-related disease burden caused by T2DM, CVD, and cancer [58]. However, between the potential direct effect of a policy and a specific health outcome is a complex causal[6] pathway that potentially includes supply-side factors from food producers, but is always connected to the diet intake behavior of individuals, direct cardiometabolic mediators, and eventually weight gain or loss [99, 106, 214]. Therefore, evaluations of diet policies can potentially assess an array of outcomes with varying proximity to the policy and health [214, 215]. Additionally, because the effect of diet on NCD health outcomes typically evolves slowly over time as individuals accumulate risk, the concrete health effects of a specific diet policy and associated economic impacts may occur only many years after the policy has been implemented [169, 215, 216].

Owing to this complexity and the fact that public policy decisions can typically not be randomized between different parts of a population, an application of the gold-standard method for the identification of causal effects of interventions – randomized controlled trials – is infeasible for the evaluation of population-based diet policies [212, 217]. Additionally, the experimental study of the effect of diet policies on health outcomes would likely be unethical because of the need for a long study duration and infeasible due to resource limitations. An exception to this are specific setting-based policies such as school nutrition standards [218, 219].

1.5.2. Quasi-experimental approaches to the evaluation of diet policies

Quasi-experimental methods are a partial remedy to this problem as they enable the identification of causal effects of policies based on observational data in non-randomized settings [220, 221]. Quasi-experimental evaluation methods such as difference-in-differences (DiD), regression discontinuity designs (RDD), and instrumental variable (IV) regression exploit the fact that the exposure to an intervention or policy is probabilistic (i.e., natural experiment) and can be as good as randomized under certain circumstances related, for example, to intervention timing, geographic restriction, or individual eligibility [220–222]. Thus, using these methods, the causal effect of a policy compared with a hypothetical counterfactual without implementation of the policy can be estimated within the Neyman-Rubin potential outcomes framework [222]. The application of these classical econometric methods has gained increasing attention in public health and epidemiology over recent years and can provide robust evidence on short-term and intermediate policy impacts if relevant assumptions can be tested and hold [223–225].

However, it is not possible to evaluate long-term policy impacts with these empirical methods because their underlying identifying assumptions are usually violated over long time frames due to time-varying confounding, secular trends, and the potential for other unknown factors to affect the outcomes of interest in the population [215, 220]. Additionally, quasi-experimental approaches can only be used when diet policies are already implemented and enough observational data have accumulated. This may lead to populations being exposed to ineffective or even harmful policies until evaluations can be conducted *ex-post* and prohibits the comparison of several proposed policy approaches to provide timely guidance for decision makers *ex-ante* [215].

Thus, the robust evaluation of population-based diet policies and consecutive policy recommendations necessitates the application of a diverse set of methods providing direct and indirect evidence on the various impact dimensions of policies [214, 215]. For example, for a given context where the implementation of a certain policy is discussed, estimates from quasi-experimental methods can provide indirect evidence on short-term effectiveness based on observed data from another context in which the policy is already implemented (*ex-post*) [215, 226]. However, other approaches, such as simulation modeling studies, can contribute additional valuable information in this situation by providing context-specific, direct evidence on the potential long-term health and economic effects (*ex-ante*), albeit not relying on actually observed policy effects [215, 226, 227].

[6] For a brief discussion of methodological challenges in estimating causal effects of the relevant epidemiological pathways, see Section 1.3.2, Section 1.6.3, and Section 6.

1.6. Simulation modeling for diet policy evaluation

1.6.1. What is simulation modeling?

Very generally, in simulation modeling, a real phenomenon or process is abstracted to its core elements and causal pathways, which are described in a logical mathematical framework [228–230]. Using computational techniques, this process can then be simulated and analyzed [228–230]. Building a simulation model is typically a long, iterative process that involves understanding the key qualitative elements of the phenomenon to be modeled, defining the scope of the model, building the respective logical model structure, making and explicitly justifying necessary assumptions, quantifying the hypothesized causal relationships, implementing the model in code, testing the model, performing calibration procedures, and validating the model, ideally on external observed data [216, 230–233].

While all simulation models are typically "wrong" in the sense that they are necessarily unable to capture the full complexity of reality and make simplifying assumptions, well validated models can be useful to analyze outcomes over long time horizons, incorporate core uncertainties, identify data gaps, and challenge prevailing theory [234, 235]. However, it has to be noted that simulation modeling is a highly resource intensive-process due to the complexity of some modern model types and often high data requirements. This complexity and explicit as well as implicit assumptions in modeling studies make transparency and replication particularly important but challenging [230, 233, 236–238].

1.6.2. Simulation modeling in health

While mathematical simulation modeling originated in the natural sciences and engineering research, with applications in, for example, climate, transport, or electrical systems modelling, it has since also been established in health research to simulate disease progression, dynamics, and outcomes over time [229, 233, 239, 240]. Simulation models in health play an important role in decision analysis and economic evaluation of new interventions as they enable the easy and prospective comparison of relevant alternatives [228, 230, 233]. Modeling studies have, for example, been used to evaluate the (cost-)effectiveness of screening programs for T2DM, CVD, lung cancer, and breast cancer [241–244]; to analyze the effectiveness of malaria and human immunodeficiency virus (HIV) treatment and prevention measures [245–247]; to assess the (cost-)effectiveness of vaccines [248]; to analyze COVID-19 transmission and the effectiveness of containment measures [249, 250]; and to model T2DM and its long-term cardiovascular complications [238, 251–253]. Results from simulation models also have an established role in Health Technology Assessment (HTA) to assess the long-term implications and cost-effectiveness and budget impact of new pharmaceutical interventions in market access procedures [254]. For example, the UK National Institute for Health and Care Excellence (NICE) considers evidence from cost-effectiveness modeling studies in their regulatory decisions [255].

Because simulation modeling of health encompasses a large variety of different model types, computational approaches, and modeling techniques, their description is beyond the scope of this introduction and available, for example, in [230], [216], [233], [256], and [257]. Additionally, each model type is subject to specific inherent assumptions, data requirements, and application domains necessitating the consideration of respective idiosyncrasies [216, 230]. To account for this, the International Society for Pharmacoeconomics and Outcomes Research (ISPOR) established a task force on Good Research Practices in Modeling Studies in the year 2000, which has published extensive guidelines for simulation modeling research in general and some common model types [228, 236, 237, 240, 258–260]. However, while guidance for modeling studies of specific exposures (e.g., tobacco) and diseases (e.g., diabetes) exists, good practice recommendations are not always available for all disease-exposure domains or model types, impeding quality assessment [238, 261].

1.6.3. Public health economic modeling of diet policies

Simulation models to assess health policies outside the traditional focus on more clinical applications and healthcare systems were already conceived in the 1990s (e.g., the Population Health Model (POHEM) in Canada) [262]. However, the development and application of these models to evaluate population-based public health policies, such as those aiming to improve unhealthy diets and prevent obesity, has only gained increasing attention more recently [227]. Here, simulation models can provide a methodological framework to leverage established epidemiological principles and available knowledge on the (assumed causal) risk factors in the etiology of NCDs to *ex-ante* assess long-term context-specific health and economic impacts of policies [215, 216, 227, 231, 233, 256]. To do so, they combine data from a variety of sources, such as epidemiological surveillance, official demographic statistics, research on the risk factors for relevant NCDs, and insights on (hypothesized) policy mechanisms [215, 216]. Such models can also flexibly integrate information on HRQoL, relevant healthcare costs and productivity losses associated with diseases (i.e., public health economic models) as well as assess the equity and wider societal impacts of the analyzed policies including those on the environment [216, 227, 231, 263].

Thus, simulation modeling studies can address some of the outlined challenges in estimating the effectiveness of population-based diet policies by accounting for complex population dynamics and the time lag between policy implementation, disease outcomes, and economic impacts connected to the chronic, slowly progressing nature of NCDs [215, 216, 227, 231]. Results from such studies are important to communicate key information about the expected impact of proposed public health policies together with the underlying uncertainty to stakeholders, including health policymakers, the media, and the public [227]. Thus, by comparing alternative policy scenarios and quantifying the long-term societal benefits of NCD prevention, they can make an important contribution to informed priority setting in obesity prevention and public health policy in general [215, 227, 261].

Landmark projects in which simulation modeling played a pivotal role to assess and compare the health, economic, and equity impacts of population-based strategies to improve diets and prevent NCDs include, for example, the Assessing Cost-Effectiveness in Prevention (ACE-Prevention), Assessing Cost-Effectiveness in Obesity (ACE-Obesity), and Burden of Disease Epidemiology, Equity and Cost-Effectiveness (BODE^3) studies in Australia, which used a suite of proportional multi-state life table Markov cohort (MSLT) models, and the Food Policy Review and Intervention Cost-Effectiveness (Food-PRICE) and Cost Effectiveness of Childhood Obesity Interventions (CHOICES) projects in the US which developed and applied complex microsimulation models [185, 233, 256, 264–270].

However, several methodological aspects regarding the application of public health economic simulation models to diet policies are important to consider and remain relatively unexplored compared to other research fields where modeling studies are important.

First, researchers can choose between several available model types, structures, and population resolutions (e.g., cohort versus individual) to analyze a particular diet policy, each with their own inherent assumptions [216, 258, 260]. These choices may have important implications for the projected impacts of policies, but comparative modeling studies or cross-validations[7] between different models in diet policy evaluations are very rarely published [216, 236, 272–274]. In other areas, model comparison is well established and deemed important [238, 241, 247, 253].

Second, beyond model types and structure, researchers can choose from a large number of studies, such as meta-analyses and cohort pooling projects, to inform the etiological effect estimates of dietary risk factors and clinical mediators on disease outcomes [132, 246, 275, 276]. As discussed, these estimates, although assumed to be causal, are most likely still subject to residual confounding despite extensive adjustment [110–113, 277]. Additionally, depending on their availability, several effect estimates for the diet policy of interest may exist with varying validity and uncertainty, potentially leading to many related assumptions.

Importantly, the structural uncertainty arising from these considerations has rarely or not at all been considered in previous applications of simulation models to evaluate diet policies [237, 253, 272, 278].

[7] The term *cross-validation* in simulation modeling is used differently than in a typical data science context and does not denote procedures to test the performance of a model on a dataset that was not used to fit the model. Rather, it indicates addressing the same question with two different models using the same inputs. For reference, see [271].

1.7. Important contextual factors in Germany

In light of the nutrition transition and the need to identify cost-effective approaches to address the societal burden of NCDs, four national contextual factors are important in Germany:

First, obesity prevalence in Germany, which follows a substantial socioeconomic gradient, is continuously increasing: over 50% of the population are overweight, and 19% are obese [279, 280]. At around 10%, the prevalence of T2DM is also high and projected to increase further over the coming decades [281, 282]. Compared to recommendations from the German Nutrition Society, the average German diet is considered relatively unhealthy, particularly because of high consumption of processed meat and low consumption of fruit and vegetables [283]. The percentage share of sugar in the daily energy intake is also above international recommendations [284, 285]. This is likely partially related to a relatively high intake of SSBs, particularly among younger age groups and men [283, 286]. According to the German Non-alcoholic Beverages Trade Association[8], the per capita consumption of drinks that are categorized as SSBs has remained relatively stable over recent years and was around 70 liters (l) per year in 2021 [287].

Second, improvements in CVD mortality rates and life expectancy have also been slowing down in Germany, which, as described above, may be related to unhealthy diets, obesity, and T2DM [42, 43, 168]. Additionally, overall life expectancy in Germany is poor compared to other highly developed nations, healthy life expectancy (HLE), 67 years for women and 65 years for mean in 2020, is actually decreasing, and regional inequalities in most health indicators between the former East and West Germany still persist since national reunification in 1990 [39, 42, 288–291]. Further, considering that Germany has a high old-age dependency ratio and that one-third of the population will be older than 60 years by 2035, the health, multimorbidity, and economic burden associated with NCD is a tremendous challenge for the German social security and statutory health systems as related medical expenditures and productivity costs resulting from disability and premature mortality are effectively paid by society [22, 28, 158, 292–299]. For example, it has been estimated that the national annual direct and indirect costs of obesity in 2010 were around €63 billion (around 21% of the total healthcare expenditure in 2010) [297, 300].

Third, Germany does not have a comprehensive policy approach to address unhealthy diets and obesity [301]. The current national strategy to reduce sugar, salt, and saturated fat in processed foods, which was announced in 2015, is based on voluntary agreements to reformulation by the food industry [302, 303]. Despite continuous monitoring of product categories targeted by this national strategy, which comes to the conclusion that only little progress has been achieved thus far, an independent evaluation of the current policy approach with different data sources and a comparison to potential alternatives is not available [304–306]. Previous research has already suggested that voluntary targets for reformulation are typically less effective than setting and enforcing mandatory targets [194]. The national reduction strategy is also in contrast to a comprehensive report published by the scientific advisory board of the German Federal Office for Agriculture and Food released in 2020, which provided detailed policy recommendations, including the taxation of SSBs, on how to make the German food system more sustainable and healthier [307]. However, in 2022, it was announced that the current German government was preparing a new national policy strategy on food [308].

Fourth, currently implemented, recommended, or discussed population-based policies to prevent the NCD burden related to unhealthy diets and obesity in Germany are not regularly evaluated and compared *ex-ante* with regard to their long-term health, economic, and wider societal impacts. As discussed, the availability of this type of information can play an important role for decision makers and is vital to support efficient evidence-based public health policy priority setting. The absence of studies providing this knowledge also is partly related to the fact that a national public health economic modeling infrastructure is not available. Existing models, such as the DYNAMO-HIA model, are comparatively old, often not actively developed, based on a structure that can not be flexibly extended, and not able to incorporate economic impacts in their current form [309].

[8]Original German name: *Wirtschaftsvereinigung Alkoholfreie Getränke (wafg)*.

1.8. The Policy Evaluation Network project

As outlined, a comprehensive policy approach is needed to improve population diets and health behaviors more generally but identifying policies and interventions that effectively increase the healthiness of diets and reduce obesity is an enormous challenge. In particular across the EU, research on the implementation and effectiveness of public health policies addressing unhealthy diets, physical inactivity, and obesity is scarce [310].

To address this gap, 29 research institutions from seven European countries and New Zealand came together in 2018 under the umbrella of the Policy Evaluation Network (PEN) consortium funded through the EU Joint Programming Initiative on a Healthy Diet for a Healthy Life (JPI HDHL) [310]. PEN is a multi-disciplinary research network with the vision of improving the health of European citizens by providing tools to guide the development, implementation, and evaluation of policies that address physical inactivity, unhealthy diets, and sedentary behavior [310]. An overview of PEN, its aims, objectives, methods, and results is accessible on the project website www.jpi-pen.eu and in [310].

Within this scope, the PEN Work Package (WP) at the Institute for Health Economics and Healthcare Management (IGM) at the Helmholtz Zentrum München[9]was responsible for examining, critically assessing, and refining the quantitative methods needed to evaluate the impact of policies together with partners from the University of Bologna, Italy. Resonating the previously described challenges in the evaluation of diet policies, the WP was structured along (1) the *ex-post* evaluation of policies using observational data and quasi-experimental methods and (2) the *ex-ante* evaluation of the long-term impact of policies using simulation modeling methods. The common goal of the collaborators in PEN WP3 was to advance both sets of methods and provide applied examples that are relevant for EU policymakers with reference to specific case studies. While the development and application of *ex-post* evaluation methods was the responsibility of the collaborators at the University of Bologna, Italy, the team at IGM/the Technical University of Munich (TUM) was responsible for the development and application of *ex-ante* simulation methods.

These circumstances provided the starting point for this dissertation.

[9]The IGM was discontinued in September 2020. The work for the project was continued at the Professorship of Public Health and Prevention (PHP) at TUM after Professor Michael Laxy's tenure track appointment at TUM.

2. Aims and objectives

This dissertation was conducted in accordance with the vision of the PEN project to provide EU policymakers with the tools and knowledge to make evidence-based decisions on public health policies addressing unhealthy diets, physical inactivity, and obesity [310]. Specifically, this dissertation aimed to contribute to the methodological advancement and application of simulation modeling methods to evaluate diet policies and to use these methods to conduct a best-practice policy evaluation of a diet policy in Germany as a PEN case study. With this, we further aimed to promote the integration of simulation models in the methodological toolbox for public health policy evaluation in the EU among PEN collaborators and beyond. To achieve this, the following concrete objectives were pursued in this dissertation:

Objective 1: Map the existing literature on the application of simulation modeling methods to evaluate the health and economic impact of diet policies.

Objective 2: Select, adapt, and further develop two internationally established simulation models for the German context to enable model comparisons and cross-validation. This includes model parameterization and input data estimation from secondary sources.

Objective 3: Conduct an evaluation of the long-term health and economic impact of an exemplary diet policy with relevance to public health in Germany.

Importantly, the above defined objectives are not independent but interlinked in a way that the methodological steps of each consecutive objective depend on the outcomes of the previous one. Therefore, the explicit analytical steps executed for this dissertation needed to be developed iteratively (see Appendix F for the original dissertation proposal). Thus, the research process followed in this dissertation is transparently described in the next chapter before we provide a summary of the methods and results.

3. Dissertation overview

This chapter gives an overview of the work conducted for this dissertation taking the research process into account and making all related decisions transparent. In this section, the relevant methods, results, and their implications are only mentioned briefly if needed and covered in more detail in the next section.

The foundational step of this dissertation was to map and review the applications and methods of simulation models for the economic evaluation of diet policies (Objective 1). We[10] developed a protocol for a systematic scoping review of the relevant literature following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for scoping reviews PRISMA-ScR [311]. The protocol was published prospectively on the repository of the Open Science Framework (OSF) on February 4, 2020 (osf.io/63kpu). In the mapping, we focused on two key questions that were not adequately researched up until this point:

1. Which applications of simulation models to evaluate diet policies exist?
2. What simulation modeling methods are used, how are they implemented, and what are their strengths and limitations with respect to the evaluation of diet policies?

This study was published in *Advances in Nutrition* (Impact Factor (IF): 9.3)[11] in April 2021 (10.1093/advances/nmab028) and is available as Additional Publication 1[12]in Appendix A. By critically examining the studies included in the review and their methods, we could collect information on suitable simulation models for our own application (Objective 2 and Objective 3).

In the review, we identified two widely used simulation models with different methodological approaches that were suitable to achieve our objectives: (1) The $\text{IMPACT}_{\text{NCD}}$ microsimulation modeling framework developed by Chris Kypridemos at the University of Liverpool, UK [312, 313]; and (2) PRIMEtime, a proportional MSLT cohort model developed by Peter Scarborough and Linda Cobiac at the University of Oxford, UK [256, 314–317]. Both models or their predecessors have been applied in landmark research projects on obesity prevention and diet policy evaluation, such as the Australian ACE-Prevention project and the Food-PRICE project in the US [265–267]. Access to $\text{IMPACT}_{\text{NCD}}$ was possible through its open access license and a collaboration with Chris Kypridemos, which we initiated in late 2020. Access to PRIMEtime and its predecessors was possible through Linda Cobiac, who was part of the thesis advisory committee (TAC) from 2019 to July 2021 as an external advisor[13], and her Australian collaborators.

In early 2020, the dissertation process was disrupted by the beginning of the COVID-19 pandemic, which led to delays due to a temporary shift to new projects related to the pandemic and personal adjustments to the new circumstances under virus containment measures. Fortunately, the overall impact of the COVID-19 pandemic was limited as no primary data collection was necessary to achieve the dissertation objectives. However, the pandemic still had direct and indirect effects on several research activities throughout the years from 2020 to 2022, as planned international travels and a research stay with the Universities of Liverpool and Oxford had to be postponed.

[10] The academic *we* is used throughout this dissertation to represent the fact that the research in this dissertation was only possible through collaboration with many great colleagues, which, however, change between studies. In some exceptions the first person is used.

[11] Based on the Clarivate Journal Citation Reports™ for the most recent year (2022) retrieved from https://jcr.clarivate.com/jcr/home.

[12] Literature reviews do not count for the formal requirements of the Ph.D. program *Medical Research in Epidemiology and Public Health* at the Ludwig-Maximilian University of Munich (LMU).

[13] For personal reasons, Linda Cobiac resigned from the TAC in 2021 and was replaced by her colleague Peter Scarborough from the University of Oxford.

In mid-2020, Professor Michael Laxy and I started co-supervising Andreea Felea as a master's student in a prototype application of a simple MSLT model (a predecessor of PRIMEtime) to the taxation of SSB in Germany after a request from Matthias Staudigel, an agricultural economist from the School of Management at TUM [256]. The model was provided by Jaithri Ananthapavan, who was a former colleague of Linda Cobiac at Deakin University in Australia. This provided the opportunity to gain hands-on insights into some simulation modeling principles, the data requirements of this model type, and to make a first step toward the identification of relevant German data sources.

In late 2020, we decided to pursue a full adaption of the $\text{IMPACT}_{\text{NCD}}$ microsimulation to Germany as the first step to achieve Objective 2. Importantly, in agreement with the TAC, the additional adaption of the PRIMEtime model was decided to be conditional on finishing $\text{IMPACT}_{\text{NCD}}$. We developed a plan to adequately address all necessary steps for an application of the model in Germany. In this process, we applied for data from the *Kooperative Gesundheitsforschung in der Region Augsburg* (KORA) and *Nationale Verzehrsstudie II* (NVS II) studies to parameterize the model with the usual dietary intake of the German population [283, 318]. Based on the considerations outlined in Section 1.7, we further decided at this time to model the impact of SSB taxation in Germany as the case study for Objective 3. Taxation of SSBs was also one of the PEN policy priorities on account of their potential role in the rise in obesity across the EU and in Germany [149, 310].

During the input data estimation procedures in 2021, we identified a lack of German national projections for CVD mortality, which are important in light of population aging and slowing mortality declines (see Section 1.7) [42, 288]. As these projections are an important input for many simulation models in general and $\text{IMPACT}_{\text{NCD}}$ specifically, we produced our own estimates. Filling a gap in the literature, we also separately projected mortality from CHD and stroke for the former East and West Germany to analyze the future development of persistent historical inequalities in CVD mortality [319, 320]. The results of these efforts were published in the *International Journal of Cardiology* (IF: 3.5) on September 11, 2023 (10.1016/j.ijcard.2023.131359, see Publication 1).

Together with our PEN WP3 partners from the University of Bologna, Italy we organized two public workshops on diet policy evaluation with both *ex-ante* simulation modeling and *ex-post* quasi-experimental methods at TUM and in Rimini, Italy, in 2021. The proceedings of these workshops are available at osf.io/fnmgk and osf.io/azf3n.

Based on the discussions at both workshops, we identified the need for a more comprehensive approach to policy evaluation and subsequently developed a manuscript on the challenges and synergies of *ex-ante* simulation modeling and *ex-post* quasi-experimental methods (see Section 1.5). This work was published in the *European Journal of Public Health* (IF: 4.4) as part of a PEN special issue on November 29, 2022 (10.1093/eurpub/ckac051) and is available as Additional Publication 2 in Appendix A. In 2023, I received the RIGorous inference in Obesity Research (RIGOR) award for this publication, which is endowed with $2,500 and a lecture[14].

To adequately model a tax on SSBs in Germany, ideally context-specific policy effect estimates are needed. Based on the mapping in Objective 1, we identified that (if no effect estimate from observational studies was available) fiscal policies were mostly modeled with price elasticities[15] of demand, which can be estimated using economic modeling techniques [215, 321].

However, price elasticities for different non-alcoholic beverage sub-categories in Germany did not exist. We therefore continued our collaboration with Matthias Staudigel and Professor Jutta Roosen from the School of Management at TUM, starting a new project in 2021 to estimate national elasticities of non-alcoholic beverages in Germany. The analysis was based on the 2013 and 2018 waves of the German Income and Consumption Survey (ICS) (*Einkommens- und Verbraucherstichprobe*), which is a nationally representative household consumption survey. A manuscript with the results of

[14] The award is given out as part of the yearly short course "Strengthening Causal Inference in Behavioral Obesity Research", which is funded by the National Institutes of Health (NIH) and organized by the Indiana University School of Public Health-Bloomington, the University of Arkansas for Medical Sciences, and the University of Alabama at Birmingham. A recording of the RIGOR award lecture is freely accessible at https://iu.instructure.com/courses/2197418/pages/rigor-presentation-%7C-speaker-karl-emmert-fees-2?module_item_id=30977437.

[15] Price elasticities indicate how the change in price of a good translates to a change in consumption of the same or (an)other (substitute) good(s).

these analyses is in preparation for submission to *Food Policy* (IF: 6.5) and is available as Additional Manuscript 1 in Appendix B.

Based on the scoping review and during discussions with PEN collaborators we identified another important research gap. We found that the influence of structural uncertainty from assumptions and decisions made by researchers conducting simulation modeling studies was barely explored but repeatedly mentioned as important to consider [237, 253]. After several iterations and delays from 2021 to 2023, we therefore repurposed the simple MSLT cohort model previously used by Andreea Felea (see above) to explore the impact of common modeling assumptions on implementing the policy mechanism of SSB taxation. The resulting study was submitted to *BMC Public Health* (IF: 4.5) on September 8, 2023 and is currently in preparation for re-submission after peer-review with only few necessary revisions. The originally submitted manuscript version is available as Additional Manuscript 2 in Appendix B.

In May 2022, a six-month research stay took place with the Universities of Liverpool (four months) and Oxford (two months). The goal of the exchange was the hands-on adaption and development of the $\text{IMPACT}_{\text{NCD}}$ microsimulation in Liverpool and the PRIMEtime model in Oxford. Both models were successfully adapted to the SSB tax case study and the German population, and extensive validation and calibration was performed at the end of 2022.

During 2022, we were also involved in a study led by colleagues from LMU, which descriptively compared changes in the sugar content of SSBs based on different policy approaches in the UK (i.e., taxation of SSBs based on sugar content) and Germany (i.e., voluntary industry reformulation). The results of this study were published in the *Annals of Nutrition and Metabolism* (IF: 3.9) on February 21, 2023 (10.1159/000529592, see Publication 2). In addition to the newly estimated elasticities, this provided the opportunity to use the estimated reductions as a further effect estimate in our case study evaluating the impact of SSB taxation in Germany (Objective 3).

Combining the results of the previous work, we conducted the case study on the impact of SSB taxation in Germany at the beginning of 2023. In contrast to the original proposal (see Appendix F), we decided to combine the model comparison and cross-validation of the newly developed $\text{IMPACT}_{\text{NCD}}$ Germany model and PRIMEtime with the case study application because a separate methodological publication was deemed very time and resource consuming by the TAC. Our study assessing the health and economic implications of SSB taxation in Germany from healthcare and societal perspectives with $\text{IMPACT}_{\text{NCD}}$ Germany and PRIMEtime models was published in *PLOS Medicine* (IF: 15.8) on November 21, 2023 (10.1371/journal.pmed.1004311, see Publication 3).

The study received considerable media attention in Germany and was covered in many regional and national newspapers. Throughout November and December, we had more than 15 radio, television, and podcast appearances related to the study[16]. In addition, I was invited to contribute to the 2024 edition of the German journal "Lebendige Wissenschaft Diabetologie - Innovationen und Auszeichnungen 2024" (see Appendix G), which is an annual publication for the conference of the German Diabetes Association (*Deutsche Diabetes Gesellschaft*).

In the next chapter, the methods and results of the research conducted to achieve the objectives of this dissertation are summarized.

[16]See for example www.ndr.de/nachrichten/info/epg/Cola-Limo-und-Co-Macht-uns-eine-Zuckersteuer-gesuender,sendung1399282.html, www.ardaudiothek.de/episode/das-interview/was-bringt-eine-zuckersteuer/mdr-aktuell/12928209/, www.br.de/nachrichten/wissen/zucker-sondersteuer-koennte-milliarden-gesundheitskosten-sparen,TwJppVw, and www.br.de/mediathek/podcast/das-verbrauchermagazin/viel-zu-suess-welche-folgen-der-uebermaessige-konsum-von-softdrinks-haben-kann/2088691.

4. Summary of methods and results

As specified in Chapter 2, the objectives of this dissertation were (1) to map the existing literature on the application of simulation modeling methods to evaluate the health and economic impact of diet policies; (2) to select, adapt, and develop two established simulation models for the German context enabling model comparison and cross-validation; and (3) to evaluate the long-term health and economic impact of a public health relevant exemplary diet policy in Germany.

The studies conducted to achieve these objectives, their main methods, key results, and important implications are summarized in this chapter. I focus here on the logical order of the conducted work irrespective of publication status or study type (see Chapter 3 for further explanation). However, in doing so, I provide more detail on the three main publications of this dissertation (see Part 2) and only very briefly summarize the additional publications and manuscripts (see Appendix A and Appendix B in Part 3). To focus on the content and because all relevant information is summarized from the respective publications and manuscripts, only key literature references are included in this chapter. Further I refer the reader to the respective publications and manuscripts for the strengths and limitations of the respective studies. The overall strengths and limitations related to this dissertation are summarized in the next chapter.

4.1. Systematic scoping review of the literature

To achieve Objective 1 and subsequently provide the basis for Objective 2 and Objective 3, we first conducted a systematic scoping of studies that applied simulation models to perform economic evaluations of population-based diet policies [322]. With this, we filled an important gap in the literature as there were many applications of simulation models in this field, which however had only been reviewed within a narrower scope (e.g., policies aiming to reduce salt intake) or together with observational studies [194]. However, the literature on the application of simulation models to assess health economic impacts of diet policies and important related methodological aspects had not been summarized, appraised, and discussed.

In the review, we identified a large number of relevant modeling studies, primarily from anglo-saxon HIC countries, which evaluated a broad spectrum of policies including health promotion, point-of-purchase information, reformulation, and fiscal policies. Although we found that models often did not capture the complexity of dietary behavior, the food groups and nutrients targeted by these policies generally included those with established public health relevance. Disease outcomes included major diet-related NCDs, primarily CVD, diabetes, and cancer, which were typically modeled via the effect of diet on key intermediate clinical risk factors, such as BMI and blood pressure. Most studies only included policy effects on healthcare costs but not wider economic impacts such as productivity losses. We classified the applied simulation modeling approaches into four types including cohort- and individual-level models with distinct assumptions, data requirements, and flexibility in extension. We also identified several important areas for future research, which included the assessment of equity impacts; the consideration of uncertainty from structural assumptions; the improvement of etiological effect estimates; devising quality standards in diet policy modeling; and increasing standards for validation and transparency.

The systematic scoping review was published in *Advances in Nutrition* in 2021 (10.1093/advances/nmab028) and is included as an additional publication in this dissertation. An extended summary of the methods and results, as well as the full study, are available under Additional Publication 1 in Appendix A.

4.2. Selection of simulation model and policy application

During the systematic scoping review, we identified suitable models for an adaption to the German context (Objective 2 and Objective 3). We contacted the corresponding authors of several modeling studies to explore possible collaborations and gather information on prerequisites for accessing the respective simulation models applied in those studies. These included Thomas A. Gaziano from Harvard University, US for the CVD PREDICT model, Jaithri Ananthapavan from Deakin University, Australia, for the CRE-Obesity model, and Chris Kypridemos from the University of Liverpool for the $\text{IMPACT}_{\text{NCD}}$ microsimulation [185, 270, 312, 313]. We also gained access to the PRIMEtime model, which is an established multi-purpose NCD prevention cohort model developed by Linda Cobiac and Peter Scarborough at the University of Oxford, who were part of the TAC [272, 314–317].

We selected the $\text{IMPACT}_{\text{NCD}}$ microsimulation, which has previously been applied in multiple countries to assess the impact of prevention policies, as our primary model and started a collaboration with Chris Kypridemos [266–268, 312, 313, 323]. The newest iteration of $\text{IMPACT}_{\text{NCD}}$ that we used is based on a modern, highly flexible, and capable framework implemented in *R* and *C++*. The PRIMEtime model, which is an MSLT model implemented in Microsoft *Excel*, was decided on as the second model [314]. This also ensured that we exploited synergies in input data estimation as the individual-level $\text{IMPACT}_{\text{NCD}}$ model requires more granular data inputs than the cohort-based PRIMEtime model.

The structure and data inputs of a simulation model necessarily depend on the policy question or modeling application at hand. As outlined in Chapter 3, we selected the taxation of SSBs as the exemplary diet policy to be evaluated in Germany early after starting adaption and development of the simulation models (Objective 3). This was based on several considerations as outlined throughout Chapter 1: SSB taxation (1) was one of the PEN policy priorities, (2) is a WHO "best-buy" policy, and (3) was recommended by a 2020 report from an official scientific advisory committee to the German government [189, 307, 310]. Additionally, the current government was preparing a new national food strategy in 2023 [308]. The focus on SSB taxation implied a particular focus on the modeling of obesity, T2DM, and CVD. Starting from this reified research objective, we developed a plan to gather the required national data inputs.

In the next section, the methods and results of stand-alone research that was directly related to the estimation of input parameters for the newly developed $\text{IMPACT}_{\text{NCD}}$ Germany microsimulation model and PRIMEtime are summarized[17].

4.3. Estimation of microsimulation model input parameters

To successfully adapt $\text{IMPACT}_{\text{NCD}}$ and PRIMEtime to Germany, all required input parameters needed to be collected, harmonized, processed, and sometimes de-novo estimated (Objective 2 and Objective 3). This included, for example, context-specific risk factor distributions, epidemiological baseline data, demographic characteristics, health economic data, and policy effects. A conceptual depiction of the needed input parameters is displayed in Figure 1. The complete list of input parameters that were used in this dissertation, including a detailed description of all estimation procedures, is available in the supplementary material of the published application of the $\text{IMPACT}_{\text{NCD}}$ Germany microsimulation (see Publication 3).

4.3.1. Projecting cardiovascular mortality in Germany

Mortality rates of CHD and stroke, and particularly their projections across future periods, are a very important input parameter for the $\text{IMPACT}_{\text{NCD}}$ model and additionally serve as calibration targets (see Figure 1 and Publication 3). As we did not identify any recent forecast for both diseases beyond the projections produced in the Global Burden of Disease (GBD) study, we opted to produce

[17] In contrast to $\text{IMPACT}_{\text{NCD}}$, the structure of PRIMEtime was not changed and only necessary population inputs were updated

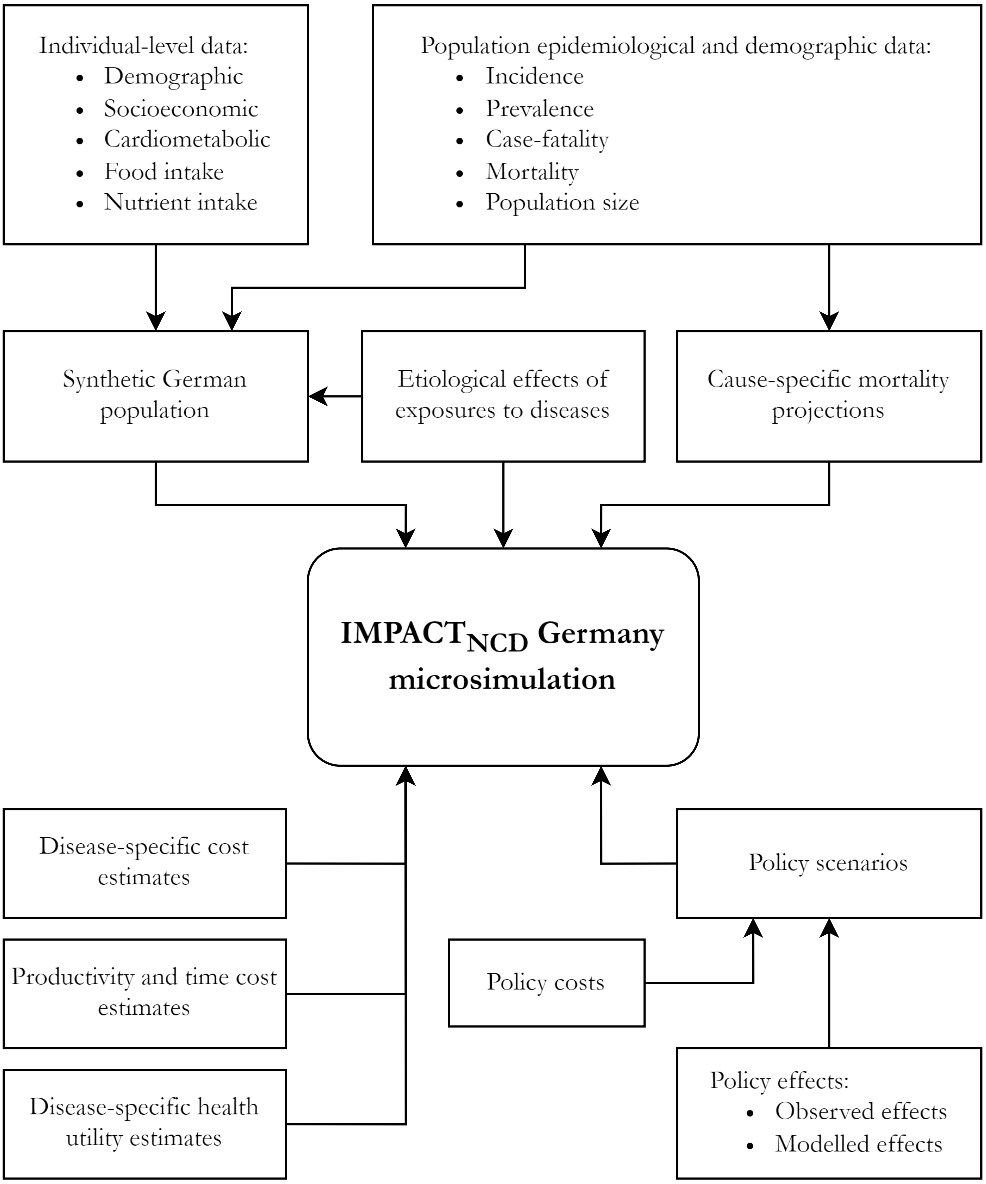

Figure 1. Conceptual overview of input parameters for the $\text{IMPACT}_{\text{NCD}}$ Germany microsimulation.

our own estimates of future mortality rates. The prevailing rationale here is that the GBD study prioritizes global consistency over national accuracy [324]. Additionally, the future implications of the recently observed slowing decline in cardiovascular mortality on the CVD mortality burden in Germany and persisting mortality inequalities between the former East and West of Germany in light of a continuously aging population had not been analyzed (see Chapter 1) [42, 288, 319, 320].

To calculate CVD mortality rates in the German adult population above age 30 years from 1991 to 2019, we used official demographic and mortality data for former East and West Germany stratified by age and sex [325, 326]. We did not include mortality data after 2019 as their inclusion would likely bias long-term projections due to several distortions related to the COVID-19 pandemic. To project trends in deaths from CVD until 2035, we applied estimates of future mortality rates from a Bayesian Age Period Cohort (BAPC) model[18] to official demographic projections [327]. We then decomposed

[18]We originally aimed to compare projection results between different forecasting methods, including a functional demographic model, to analyze the influence of their inherent assumptions. However, this approach was rejected by peer-reviewers because of the resulting uncertainty about the "correct" model. Additionally, the output of the *demography* package, which we used to estimate functional demographic models in *R*, can be used directly in $\text{IMPACT}_{\text{NCD}}$ without the need for further processing. This is not the case for the BAPC model which we estimated with the *bamp* package [327, 328].

changes in total deaths from 1991 to 2035 into interactions between changes in population size, age structure, and mortality rates and analyzed regional mortality inequalities between East and West Germany with standardized mortality ratios (SMRs) [329, 330]. To ensure the robustness of our forecasting approach, we conducted extensive model calibration to historic mortality trends based on the mean absolute scaled error (MASE) and compared the predictive performance of the BAPC to other commonly used demographic models [328].

Our analysis showed that CHD and stroke mortality rates in East and West Germany have declined considerably between 1991 and 2019, but that this decline has decelerated continuously since 2005. While we projected a decline in the number of deaths from CHD of about 10% between 2019 ($\approx 115,000$ deaths) and 2035 ($\approx 104,000$ deaths), deaths from stroke may increase by around 5% ($\approx 51,000$ deaths in 2019 to $\approx 54,000$ deaths in 2035) driven by stagnating mortality rates among men. We showed that increasing population aging together with further stagnating CVD mortality rates will likely lead to an inflection point at around 2030, after which absolute deaths from CVD in Germany increase again for the first time since 1991. Despite some convergence, CVD mortality has steadily remained higher in East compared to West Germany, and we projected that this pattern likely continues for CHD but not for stroke.

With this study, we contributed to accumulating evidence on the stagnation of CVD mortality trends, which might be responsible for slowing gains in life expectancy. Increasing rates of obesity and T2DM, which are important cardiovascular risk factors, together with diminishing returns of smoking policies, might be partially responsible for these developments. As the prevalence of obesity and T2DM is projected to increase over the next decades in Germany, our results seem plausible and convey important implications for the burden on health systems and health policy in Germany.

This study was published in the *International Journal of Cardiology* in 2023 (10.1016/j.ijcard.2023.131359) and is included as a main publication in this dissertation (see Publication 1).

4.3.2. Demand parameters of non-alcoholic beverages in Germany

Another important input parameter for the simulation of the long-term health and economic impacts of SSB taxation in Germany are context-specific estimates of the immediate effect of the policy on SSB consumption (Figure 1). Generally speaking, the immediate effects of such a tax can be estimated either using observational data from pre- and post-tax periods in a setting where the tax is already implemented or using economic demand modeling to estimate hypothetical consumer reactions to price changes in terms of price elasticities [215, 321]. Briefly, price elasticities denote how a change in the price of a product influences purchasing[19] of the same (own-price elasticities (oPEs)) or another product (cross-price elasticities (cPEs)) [321].

Because no tax on SSBs is currently implemented in Germany and as we neither identified suitable existing German price elasticities, nor wanted to rely on estimates from published international studies or meta-analysis (e.g., [186] or [200]), we decided to estimate an economic demand model of non-alcoholic beverages in Germany using the ICS (*Einkommens- und Verbraucherstichprobe*), which is a national population-representative household consumption survey. In the study, we used a linearly approximated Almost Ideal Demand System (AIDS) with adjustments for price endogeneity and censoring to estimate the demand for *flavored milk*, *plain milk*, *water*, *SSBs*, *fruit juice*, and *coffee & tea* across households with different income levels [331–334]. In addition, we simulated the purchasing and consumer welfare effects of a 20% price increase due to a tax on (1) SSBs and (2), SSBs, fruit juice, and flavored milk [335, 336].

We found that SSBs (17.9l per month) were the second most purchased non-alcoholic beverage after water (34.4l) accounting on average for 27.6% of the non-alcoholic beverage expenditure. The demand for sugary beverages was more elastic compared to other non-alcoholic beverages (oPE < -1), particularly among low- and middle-income households. A tax that increased the price of sugary beverages by 20% would result in 3.4l fewer SSBs purchased per month (Scenario 1) and additionally

[19] In nutritional epidemiology, "consumption" usually indicates actual intake, where as "consumption" in economics usually indicates purchasing of a good by a *consumer*.

slightly less juice (-1.7l) and flavored milk (-0.3l) (Scenario 2). We also found that high-income households would generally react less to the tax and therefore incur a larger proportion of the welfare loss. Additionally, taxation of sugary beverages in Germany would be regressive but, as health gains would likely be concentrated among low- and middle-income households, could in fact contribute to reducing health inequalities.

The corresponding study is currently in preparation for submission to *Food Policy* and is included as an additional publication manuscript in this dissertation. An extended summary of the methods and results as well as the full manuscript are available under Additional Manuscript 1 in Appendix B.

4.3.3. Reductions in the sugar content of soft drinks in Germany and the United Kingdom

In addition to estimates from economic demand modeling, as described above, SSB taxation scenarios in a simulation model can be informed by estimates of actually observed changes in policy-relevant endpoints (Figure 1) [215]. In the context of SSB taxes, for which the tax rate depends on sugar content, the reduction in sugar content in taxed beverages through reformulation is one of these endpoints. Examples are the UK Soft Drinks Industry Levy (SDIL), which defines tax rates according to three tiers of sugar content, or the SSB tax in France, for which tax rates increase almost linearly with sugar content [337, 338]. In contrast, the German government's current sugar reduction strategy consisted of voluntary industry agreements for reformulation [303, 304, 308]. However, to what degree this approach was effective in reducing SSB sugar content, particularly compared to other approaches, was unclear (see also Section 1.7) [305, 306].

We thus conducted a study in which we used aggregate sales and ingredient data for SSBs from the Euromonitor Passport market research database to descriptively evaluate trends in SSB sugar content from 2011 to 2021 between Germany and the UK[20] [339]. The Passport database contains information from a variety of sources such as industry reports, store audits, and official statistics and includes both store retail (e.g., from supermarkets) and hospitality sales (e.g., from restaurants and bars). The main outcomes were SSBs (in milliliters (ml)) and sugar from SSBs (in g) sold per person per day and mean sales-weighted SSB sugar content (in g per 100 ml). Per person outcomes were calculated by dividing aggregate SSB and sugar sales data by official population counts. We calculated the targets of the German sugar reduction strategy for SSBs based on 2015 levels assuming a linear decline of 15% until 2025, as specified by the German government [302, 303]. In the analysis, we primarily descriptively compared observed German trends with the targeted reduction for 2021 and UK trends by calculating absolute and relative changes in outcomes over time.

We found that, in Germany, the sales-weighted sugar content of SSBs has reduced by around 2% between 2015 and 2021. Thus, the targeted decrease in the national sugar reduction strategy of about 9% up to 2021 was not achieved. Sales of SSBs and sugar from SSBs have reduced by about 4% over the same period. In contrast, in the UK, where the SDIL was announced in 2016 and implemented in 2018, the sales-weighted sugar content decreased by 29% between 2015 and 2021. Additionally, we found that, while sales of sugar from SSBs also decreased by 28% in the UK, there was no detrimental effect on SSB sales, which actually increased by 1%. However, it has to be noted that our analyses were not able to causally attribute the observed changes to the UK SDIL or the German sugar reduction strategy. At least for the UK, other studies have reported similar reductions in SSB sugar content using different data sources.

With this study we contributed to the continued evaluation of the German national reduction strategy established in 2015 and showed that this voluntary approach to reduce the sugar content in SSBs in Germany is likely not effective. Thus, other policies, such as SSB taxation, should be considered by German policymakers to reduce sugar intake and improve population health.

This study was published in the *Annals of Nutrition and Metabolism* in 2023 (10.1159/000529592) and is included as a main publication in this dissertation (see Publication 2).

[20] A protocol for the study was published on the OSF before data analysis (osf.io/3wj49).

4.4. The health and economic impact of sugar-sweetened beverage taxation in Germany

As described in the previous sections, the objectives of this dissertation included the adaption of two simulation models (i.e., $IMPACT_{NCD}$ and PRIMEtime) to the German context (Objective 2) with the specific case study of simulating the impacts of a tax on SSBs (Objective 3). Previous studies had already used simple simulation approaches to estimate the potential impact of SSB taxation on obesity, T2DM, and caries in Germany [340–342]. However, these studies mostly neither assessed the economic impacts nor estimated the long-term health implications of SSB taxation accounting for complex demographic and epidemiological dynamics or reported their modeling approaches transparently. Our own descriptive analyses about the effectiveness of the current sugar reduction strategy (see Publication 2) and the points explained in Section 1.7 and Section 4.2 further underpinned the policy relevance of our application.

We therefore used the newly developed $IMPACT_{NCD}$ Germany microsimulation[21] to evaluate the long-term health and economic impacts of different SSB taxation scenarios based on recommendations and implemented policies (Objective 3) [189, 337]. We specifically relied here on the policy effect estimates produced in Publication 2 and Additional Manuscript 1. To increase the robustness of our results, we additionally performed a cross-validation with PRIMEtime (Objective 2), which has not been published before in population health modeling [314]. We also tried to address other scientific gaps that we identified in the systematic scoping review, such as structural uncertainty, and aimed to fulfill the highest standards with respect to validation and transparency (see Additional Publication 1) [236, 237].

We evaluated three SSB taxation scenarios: (1) a 20% ad valorem tax on SSBs; (2) a 20% ad valorem tax on SSBs and fruit juice; and (3) reduction in SSB sugar content by 30% resulting from reformulation under a hypothetical tax based on sugar content (comparable to the UK SDIL) [189, 337]. For scenarios (1) and (2), we assumed a pass-through of 82% based on international evidence [186]. We projected the health and economic effects of these policy scenarios compared to a baseline without policy from 2023 to 2043 in the German adult population aged 30 to 90 years. To achieve this, we created a synthetic German population using the best available national data sources (e.g., KORA, NVS II). The etiological pathways of the model were grounded in established epidemiological evidence from meta-analyses and seminal studies [74, 246, 267, 275, 276]. Briefly, we modeled the effects of reduced sugar intake on BMI and subsequent impacts on morbidity and mortality related to T2DM, CHD, and stroke. We additionally (1) considered BMI-independent effects of SSBs on T2DM and CHD, the influence of which we assessed in structural uncertainty analyses; and (2) as discussed, cross-validated results with the PRIMEtime model [132, 237, 314, 343]. For health economic analysis, we included healthcare, patient time, and productivity costs and calculated quality-adjusted life years (QALYs). We considered uncertainty from all possible sources, conducted extensive sensitivity analyses, calibrated the model to replicate observed mortality trends, and validated baseline projections, among others, on epidemiological data not used to inform the model inputs.

We found that intake of sugar from SSBs could be reduced on average by 1 to 5.9g (i.e., 3–17%) per day per person depending on the policy scenario. In this way, a tax on SSBs could prevent or postpone[22], for example, 132,100 to 244,100 cases of T2DM and 39,200 to 69,800 cases of CHD from 2023 to 2043. Similarly, SSB taxation could lead to 733,800 to 3,919,200 fewer years lived with obesity and result in 106,000 to 192,300 QALYs gained. These health impacts would translate to an economic impact of €9.6 to €16 billion from a societal perspective, of which €2.3 to €3.9 billion would result from cost savings in the healthcare sector. The remaining impacts would be primarily due to increased productivity as a consequence of reduced premature mortality and sick leave, but also reductions in time costs related to T2DM (e.g., self-management). We found that a reduction in SSB sugar content by 30% led to higher health and economic benefits than 20% ad valorem taxation.

[21] The source code for the model is available at github.com/kalleEF/IMPACT-NCD-Germany.

[22] Reductions in risk factors can either completely prevent the incidence of disease in a person or delay its onset. Both reduce the morbidity burden and are important outcomes for prevention.

Importantly, health and economic gains were about 10-fold higher than those expected under the current German sugar reduction strategy, which we modelled in a sensitivity analysis. Results from PRIMEtime were very similar, and our assessment of structural uncertainty indicated that policy impacts are considerably smaller, but still substantial, when excluding the direct (BMI-independent) effects of SSBs.

Our study provided concrete context-specific recommendations for German policymakers and showed that a tax on SSBs could contribute to improving population health and reduce societal costs in Germany by preventing cardiometabolic disease.

This study was published in *PLOS Medicine* in 2023 (10.1371/journal.pmed.1004311) and is included as a main publication in this dissertation (see Publication 3).

4.5. Assessing assumptions in the modeling of sugar-sweetened beverage taxes

In an additional study we explored the impact of decisions made by researchers regarding certain modeling assumptions on simulated policy impacts. This topic, which is related to structural uncertainty, was barely covered in the literature but repeatedly mentioned as as important consideration [237, 253]. We analyzed how the projected impact of a 20% ad valorem SSB tax on energy intake and consequently BMI, estimated with energy balance equations, is affected by six different policy modeling assumptions typically made by researchers [164]. These included, for example, adjusting the SSB own-price elasticity for baseline SSB consumption, using an SSB own-price elasticity from a meta-analysis of empirical studies, and implementing substitution to fruit juice based on volume [200, 341, 344, 345]. We then repurposed an existing simple MSLT model (see Chapter 3) with an easily modifiable structure to compare the resulting simulated impacts on DALYs and healthcare costs related to T2DM between modifications over the lifetime of the German adult population aged 20 years and older [256]. We found that the mean number of DALYs averted ranged from -18,000 to 164,000 depending on the respective assumption and that this structural uncertainty was similar to the variability in mean policy impacts between scenarios with alternative tax rates. Because these assumptions are made by researchers and can vary substantially between studies, the resulting uncertainty and its implications should be reported transparently.

This study is currently in preparation for re-submission after peer-review at *BMC Public Health* and is included as an additional publication manuscript in this dissertation. An extended summary and the originally submitted manuscript are available under Additional Manuscript 2 in Appendix B.

4.6. Synergies of simulation models and quasi-experimental methods to evaluate diet policies

In the PEN project, we identified a need to discuss the evaluation of public health policies addressing nutrition and physical activity within a more comprehensive approach. Although *ex-ante* simulation modeling and *ex-post* quasi-experimental (econometric) methods are well established and often applied, their potential synergies within the broader scope of policy evaluation have remained largely unexplored.

We thus conducted an integrative review on this topic, collecting and discussing seminal studies, best-practice recommendations, and the knowledge that was gained within PEN [310, 322]. Using the identified literature, we summarized the key assumptions of quasi-experimental DiD, RDD, and IV approaches and discussed analytical strategies to test them [220]. Important areas of development for future applications of these methods included the assessment of heterogeneity in treatment effects and the exploitation of novel data sources. With regard to simulation modeling we discussed different types of models, their assumptions, and data and computational requirements [216, 230]. Related challenges in the evaluation of public health policies included non-causal effect estimates, validation, and the disregard of heterogeneity in policy effects. Combining these insights, we developed a conceptual framework to integrate the strengths, limitations, and synergies of both approaches. Quasi-experimental methods are able to provide design-based causal estimates, but their assumptions do not hold over long time horizons. Simulation models, on the other hand, need these causal estimates and are able to exploit epidemiological principles to project chronic disease outcomes over several years. We therefore argued that both methods should be applied together to provide robust evidence on public health policies for policymakers and other stakeholders.

This study was published in the *European Journal of Public Health* in 2022 (10.1093/eurpub/ckac051) and is included as an additional publication in this dissertation. An extended summary and the full manuscript are available under Additional Publications 2 in Appendix A.

5. Strengths and limitations

The research approach taken in this dissertation and in the respective studies has several strengths. We conducted a set of connected studies with diverse methods spanning multiple disciplines that were partially newly developed as research and data gaps were identified. We aimed to adhere to the highest quality standards in study design, conduct, analysis, and reporting, paying particular attention to the robustness of our results. For example we devised a detailed protocol for the systematic scoping review and considered alternative model specifications in our projections of CVD mortality and in the evaluation of SSB taxation in Germany. In contrast to many previous public health modeling studies, we also conducted extensive validation analyses, assessed aspects of structural uncertainty, and made all assumptions, input data estimation procedures, and technical details of $\text{IMPACT}_{\text{NCD}}$ Germany transparently available in a detailed supplement. We also encourage other researchers to use and extend the model by making its source code publicly available. With $\text{IMPACT}_{\text{NCD}}$ Germany, we also developed the first modern and highly capable population health microsimulation for Germany. Based on our work, this foundational model can be flexibly extended to other exposures, disease areas, and policy questions beyond unhealthy diets at the intersection of public health, health services research, economics, and social policy. In particular, quantification of the wider economic impacts of prevention measures, as in our evaluation of SSB taxation, can help to make the potential benefits of population-based prevention policies salient to policymakers. As the implementation of recommended prevention policies across key domains such as diet and smoking is premature in Germany, the research conducted in this dissertation and consecutive work building on it may provide German and EU stakeholders with actionable evidence to implement effective NCD prevention strategies. Policy modeling studies can thus be a key tool to tackle future population health and health systems challenges related to NCD prevention and resource allocation in light of population aging.

However, the work in this dissertation is limited with regard to several important aspects, which we summarize briefly below[23]. First, time and resource constraints prohibited, for example, a full systematic collection and quality appraisal of etiologic effect estimates that can be used in the evaluation of SSB taxation in Germany. Thus, these important parameters were largely based on established sources such as the GBD and seminal cohort-pooling projects. Yet, these are likely the best available sources, and such an extensive task would justify a separate research project. Similarly, an in-depth dissection of all methodological differences between $\text{IMPACT}_{\text{NCD}}$ Germany and PRIMEtime was not achievable considering the broad scope of the work conducted. Owing to constraints in national data, we were also not able to assess the equity impacts of SSB taxation. Second, methods to model future health outcomes, despite their foundation in widely accepted epidemiological theory, are still inherently limited by the large factual unpredictability of the future and are thus not a magic bullet. While such projections are arguably useful in making informed policy decisions with long-lasting implications and statistical techniques can be used to acknowledge the underlying uncertainty, particularly large-scale disruptions such as the COVID-19 pandemic and technological advances with wide societal consequences can always jeopardize their validity. Third, simulation modeling of population health is still premature compared to other fields, such as engineering and the natural sciences, despite its common application. This is largely related to challenges in the availability of data measured with minimal bias and the quantification of causality in epidemiology [110, 111, 277]. For example, it is comparatively easy to obtain the energy usage data of electrical appliances for application in energy systems modeling to optimize electricity grids, whereas the accurate quantification of energy intake and expenditure in humans is highly complex, and its impact on the regulation of body weight depends on various interacting individual factors that are not yet fully understood [105].

[23] For a full account of the limitations related to each study we refer to the respective publications or manuscripts.

6. Conclusions and avenues for further research

This dissertation contributes to the continuous effort to find effective approaches to tackle the burden of NCDs in Germany, Europe, and globally. We show that, in particular, the mortality burden of CVD, which is the leading cause of death in Germany, is likely to increase in the next decades as a result of the effects of population aging and stagnating CVD mortality rates, creating enormous challenges for national health systems. As unhealthy diets are a key risk factor for CVD, T2DM, and obesity, we analyze the potential impact of population-based prevention policies that aim to improve the healthiness of diets. We find that the current German policy strategy to reduce sugar in SSBs does not seem to be effective, particularly compared to regulation in the UK where SSBs are taxed based on sugar content. Because the effects of changes in diet accumulate over long periods of time, whereas policy decisions need to be made now, we developed and applied simulation modeling methods that enable the estimation of the long-term health and economic impacts of diet policies in Germany. Using the newly developed $\text{IMPACT}_{\text{NCD}}$ Germany microsimulation model, we are able to give concrete policy recommendations by showing that the taxation of SSBs in Germany could contribute to the prevention of obesity and cardiometabolic NCDs and save several billions in healthcare costs and productivity losses from 2023 to 2043. We additionally contribute to the methodological development of simulation modeling in population health in three ways. First, in our own application, we considered aspects of structural uncertainty and cross-validated results with the independently developed PRIMEtime cohort model, which has not been done before. Second, we conducted an in-depth review of existing simulation-based diet policy evaluations pointing out important areas for further research. Third, we developed a conceptual framework to integrate quasi-experimental and simulation modeling methods for public health policy evaluation.

Lastly, we want to point to multiple avenues for further research in the area of *ex-ante* public health policy evaluation. First, despite the widespread application of simulation models to evaluate diet policies and their relevance for actionable policy recommendations, no respective guidelines exist for their conduct and reporting. Thus, quality standards should be established to increase the trust of stakeholders, which include researchers, policymakers, and the public alike. Second, there are many opportunities to extend the $\text{IMPACT}_{\text{NCD}}$ Germany microsimulation with other important NCDs, for example cancer, and their structural and behavioral risk factors to enable the evaluation of relevant prevention policies, including their health, economic, and equity impacts in Germany. Similarly, the model can be used, for example, to estimate the attributable burden of key risk factor clusters, such as unhealthy diets, under different possible population exposure trajectories. Other extensions of the model may include increasing its geographic scope and resolution to assess both EU-wide and sub-national regional differences; including an environmental module to assess the sustainability impacts of diet policies; and comparing the cost-effectiveness of NCD treatment and prevention approaches. Third, population heterogeneity in the response to public health policies should be considered and quantified more rigorously to make a more granular analysis of policies and their effects on health inequalities possible. This also includes behavioral adaption mechanisms related to, for example, changing food environments and habituation effects under newly introduced regulations. Methods like agent-based microsimulation that are able to explicitly simulate individual-environment interactions, may be particularly useful for such tasks [249, 346]. Because public health policies affect behavior and health outcomes in various complex ways, simulation models could also theoretically be used as a tool to identify factors that explain the potential discrepancy between *ex-post* observed and *ex-ante* "naïvely" simulated policy effects. Fourth, methods of causal inference that enable the estimation of causal effects on observational data can, as described, exploit many synergies with simulation modeling methods. Causal methods are needed to estimate the mentioned, potentially heterogeneous, policy effects, the health impacts of which can then be estimated with, for example, a microsimulation [347, 348]. But, as mentioned above, also, the epidemiological core parameters of simulation models in fact rely on truly causal estimates that do not suffer from confounding and other biases. Methods such as Mendelian randomization might be a remedy for this and can theoretically also enable the quantification of cumulative exposure effects, which are largely unavailable but likely play a key role in the life course etiology of many NCDs [111, 277]. Finally, to estimate wider societal consequences, population health microsimulation models could be linked with established macroeconomic productivity, labor market, and land use and climate models.

7. Author contributions and supervision

7.1. Supervision

All scientific work in this dissertation was conducted under the supervision of my TAC and particularly my primary direct supervisor Professor Dr. Michael Laxy from the Technical University of Munich, who supported me in the development of the respective research questions and the selection of adequate study designs. My secondary supervisor Professor Dr. Eva Rehfuess from the Ludwig-Maximilian University of Munich further directly supported me in the selection of the study design and conduct of the systematic scoping review (Additional Publication 1).

Publication 1 and Publication 3 were further supervised by Dr. Chris Kypridemos from the University of Liverpool, UK, who primarily contributed methodological expertise and experience in the application of the $\text{IMPACT}_{\text{NCD}}$ simulation model. Publication 3 was additionally supervised by Professor Dr. Peter Scarborough and Dr. Ben Amies-Cull from the University of Oxford, UK, who provided access to the PRIMEtime model, and supported with nutritional expertise by Professor Dr. Linseisen from the University of Augsburg and Dr. Nina Wawro from the Helmholtz Zentrum München. The idea for the integrative review of challenges and synergies in the application of quasi-experimental methods and simulation models (Additional Publication 2) was developed based on discussions we had with our PEN collaborators Professor Dr. Mario Mazzocchi and Professor Dr. Sara Capacci from the University of Bologna, Italy, and the participants in the workshops that we organized in the PEN project. The estimation of price elasticities of non-alcoholic beverages in Germany (Additional Manuscript 1) was further supervised by and conducted together with Dr. Matthias Staudigel and Professor Dr. Jutta Roosen from the School of Management at the Technical University of Munich. The study design and interpretation of the simulation study, in which we analyzed the implications of policy modeling assumptions (Additional Manuscript 2), was further supported by Dr. Jaithri Ananthapavan from Deakin University, Australia, who provided the initial MSLT model in Microsoft Excel.

7.2. First author publications

For all first author publications (see Publication 1, Publication 3, Additional Publication 1, and Additional Publication 2), I developed the research question, conceptualized the study design, conceptualized the presentation of results in tabular and graphical form, performed data visualization, interpreted the findings, wrote the first manuscript drafts, revised and edited the manuscripts, submitted the respective manuscripts for publication, implemented the changes requested by peer-reviewers, and managed the journal publication process.

In the case of empirical first author publications (see Publication 1 and Publication 3), I also acquired and managed the respective data, planned the statistical procedures and performed the data analysis. I am also the developer and maintainer of the $\text{IMPACT}_{\text{NCD}}$ Germany microsimulation model which was developed based on the $\text{IMPACT}_{\text{NCD}}$ England microsimulation model during the work for this dissertation and is publicly available in a GitHub repository.

For the two literature review first author publications (see Additional Publication 1 and Additional Publication 2), I further devised the search strategy to identify relevant studies, carried out the search in the respective electronic literature databases, screened the retrieved records, selected the eligible studies based on the predefined inclusion criteria, conceptualized and performed the extraction of study data, and performed a quality appraisal of the included studies (if applicable).

For the two publication manuscripts of which I am a shared first author (see Additional Manuscript 1 and Additional Manuscript 2), I was also responsible for or significantly contributed to the above mentioned research tasks with two important exceptions that warranted equal shared first authorship: (1) For the manuscript on non-alcoholic beverage price elasticities in Germany (see Additional Manuscript 1), a shared first authorship is justified as Dr. Matthias Staudigel was responsible for the statistical analysis and implementation of the demand model. Considering his agricultural economic expertise, we developed the study design and refined the data analysis together. I conceptualized the manuscript, interpreted the findings, wrote the complete initial draft, and am responsible for the publication process. (2) For the simulation study assessing the implications of modeling assumptions (see Additional Manuscript 2), a shared first authorship is justified because the other first author (my former master's student Andreea Felea) originally applied the used MSLT model in her master's thesis. Although parts of the model and the scope of its application have changed considerably, we think it is fair to prominently acknowledge her contribution in this way.

7.3. Co-author publications

For the co-author publication (see Publication 2), I contributed to the critical revision of the study design, supported the application of adequate statistical procedures, contributed to the interpretation of the results, critically revised and edited the manuscript draft, and supported the response to peer-reviewers in the publication process.

8. Further projects

Beyond the research conducted for this dissertation I have been involved with several other research activities within the broader scope of health economics, public health, and preventive medicine over the last five years. The full output of these activities can be seen in the list of publications included in Appendix C and is briefly summarized here.

One separate stream of work was about topics in diabetes prevention and related economic aspects. Connected to my research stay at the Emory Global Diabetes Research Center (EGDRC) at Emory University, Atlanta, US, I was involved in several analyses of the Integrating Depression and Diabetes Treatment (INDEPENDENT) study. INDEPENDENT was a multi-center, open-label, pragmatic, patient-randomized clinical trial on the effectiveness of an integrative collaborative care approach (compared to usual care) for patients with T2DM and depressive symptoms. I was the main analyst of the primary effectiveness study of INDEPENDENT, which was published in the *Journal of the American Medical Association (JAMA)* (IF: 120.7) in 2020. Additionally, I was the first author of the health economic analysis of INDEPENDENT, in which we analyzed the cost-effectiveness of the implemented collaborative care intervention. This study originated from my master's thesis and was published in *Diabetes Care* (IF: 16.2) in 2023. I was further involved as a co-author in three other studies related to the INDEPENDENT trial, which were published in *General Hospital Psychiatry* (IF: 7.0), the *Journal of General Internal Medicine* (IF: 5.7), and *Primary Care Diabetes* (IF: 2.9). Beyond this work, I was a second or third author on several studies on the prevention and management of diabetes in Germany using data from the population-based KORA platform. This included two analyses on the clinical and socio-demographic predictors of T2DM self-management and the prevalence of prediabetes (defined by different clinical thresholds), which were published in *Acta Diabetologica* (IF: 3.8) and *Primary Care Diabetes* (IF: 2.9) in 2020. A third study in which we simulated the long-term health and economic benefits of improved control of key clinical diabetes risk factors from the perspective of the German statutory health insurance (SHI) with the United Kingdom Prospective Diabetes Study (UKPDS) Outcomes Model was published in *Diabetologia* (IF: 8.2) in 2023.

I was also involved in research covering miscellaneous topics in public health and health economics. During the central phase of the COVID-19 pandemic in 2020 and 2021, I contributed my developing expertise in simulation modeling to a rapid systematic Cochrane review on the effectiveness of travel-related pandemic control measures, which at that point was predominantly evaluated with simulations. The rapid review and its update were published in the *Cochrane Database of Systematic Reviews* (IF: 8.4). In 2022, I supported a fellow Ph.D. student in the development and conduct of a scoping review on the cost-effectiveness of early-infant HIV diagnosis in LMICs, which was subsequently published in *Infectious Diseases of Poverty* (IF: 8.1). Through my membership of the section on public health economics in the European Public Health Association (EUPHA), I was invited to a commentary on the potential for the application of microsimulation methods to evaluate the health equity impact of policies, which was published in *The Lancet Regional Health – Europe* (IF: 20.9) in 2023.

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Part II.

Publications

1. Forecasting the mortality burden of coronary heart disease and stroke in Germany: National trends and regional inequalities

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Forecasting the mortality burden of coronary heart disease and stroke in Germany: National trends and regional inequalities

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A R T I C L E I N F O

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A B S T R A C T

Background: The decline of cardiovascular disease (CVD) mortality has slowed in many countries, including Germany. We examined the implications of this trend for future coronary heart disease (CHD) and stroke mortality in Germany considering persistent mortality inequalities between former East and West Germany.
Methods: We retrieved demographic and mortality data from 1991 to 2019 from the German Federal Statistical Office. Using a Bayesian age-period-cohort framework, we projected CHD and stroke mortality from 2019 to 2035, stratified by sex and German region. We decomposed annual changes in deaths into three components (mortality rates, population age structure and population size) and assessed regional inequalities with age-sex-standardized mortality ratios.
Results: We confirmed that declines of CVD mortality rates in Germany will likely stagnate. From 2019 to 2035, we projected fewer annual CHD deaths (114,600 to 103,500 [95%-credible interval: 81,700; 134,000]) and an increase in stroke deaths (51,300 to 53,700 [41,400; 72,000]). Decomposing past and projected mortality, we showed that population ageing was and is offset by declining mortality rates. This likely reverses after 2030 leading to increased CVD deaths thereafter. Inequalities between East and West declined substantially since 1991 and are projected to stabilize for CHD but narrow for stroke.
Conclusions: CVD deaths in Germany likely keep declining until 2030, but may increase thereafter due to population ageing if the reduction in mortality rates slows further. East-West mortality inequalities for CHD remain stable but may converge for stroke. Underlying risk factor trends need to be monitored and addressed by public health policy.

1. Introduction

In the past three decades, cardiovascular disease (CVD) has emerged as a major contributor to the global burden of disease. Between 1990 and 2019, the number of disability-adjusted life years attributable to stroke increased by 32.4% and coronary heart disease (CHD) by 50.4% [1].

Despite this shift to a predominance of non-communicable diseases

Abbreviations: BAPC, Bayesian age-period-cohort model; CHD, Coronary Heart Disease; CI, Confidence interval; CrI, Credible Interval; CVD, Cardiovascular disease; ESCD, European Shortlist for Causes of Death; FRG, Federal Republic of Germany; GDR, German Democratic Republic; ICD, International classification of diseases; MASE, Mean absolute scaled error; NCD, Non-communicable disease; RW, Random walk; SMR, Standardized mortality ratio; UK, United Kingdom; US, United States.

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(NCDs) driven by global population growth, population ageing and unhealthy lifestyles, age-standardized CVD mortality rates have decreased from the 1980s until recently, particularly through population-level reductions in key risk factors such as smoking and improvements in primary, secondary and tertiary prevention [2–5].

In the last few years, the continuous decline of CVD mortality has slowed or even reversed for both men and women in some high-income countries, including Germany, contributing to slowing gains in life expectancy [6–12]. Possible explanations include an increasing prevalence of obesity and its cardiometabolic effects, such as hypertension, hypercholesterolemia and hyperglycemia, stagnating reductions or increases in smoking prevalence and political inertia to tackle the underlying environmental and socio-economic risk factors such as income inequality [5,13–15].

For Germany the CVD mortality dynamic is important since over one-third of the population is expected to be older than 60 years by 2035 [16]. Moreover, before German reunification in 1990, mortality from most causes was higher in the former German Democratic Republic (GDR, East Germany) than in the Federal Republic of Germany (FRG, West Germany) [17–19]. After reunification, this mortality gap narrowed considerably, and for some age groups closed, particularly among women. This is often attributed to different factors, such as different death certificate coding procedures in the 1990's, improved access to healthcare, better living conditions, and reduced psychosocial stressors [17,20–24]. Despite the evident convergence, mortality inequalities in CVD between East and West Germany persist until today, particularly for men [17,18].

The objective of this study is to unravel the past and future dynamic between these historical inequalities, population ageing, and mortality trends. In using modern statistical and demographic methods we aim to gain insights as to whether recent global trends in CVD mortality have continued in Germany and what their future implications are. Our projections of the future mortality burden can further support health policy priority setting and resource allocation [25–27].

To achieve this, we perform three analytical steps. First, we describe past CHD and stroke mortality trends and project mortality rates including the respective future number of deaths in Germany to 2035 using a Bayesian approach which accounts for age, period, and cohort effects. Second, we use mortality decomposition methods to analyze the contribution of changes in population size, population ageing and mortality rates from 1991 to 2035. Third, we analyze regional inequalities in CVD mortality between the former East and West German states using directly standardized mortality ratios (SMR).

2. Methods

2.1. Data

We retrieved population counts from 1991 to 2019 and population count projections from 2020 to 2035 from the German Federal Statistical Office (GENESIS, www.destatis.de) by sex, single years of age and German federal state. Official population counts before 2011 were adjusted for intercensal projections using published values [28]. This was necessary because before Germany implemented its first register-based census in 2011, no census was conducted for more than two decades, leading to a substantial overestimation of the population size [28].

Official death count estimates were retrieved from the German Information System of the Federal Health Monitoring (*Gesundheitsberichterstattung des Bundes*, www.gbe-bund.de) for CHD and stroke from 1991 to 2019 as defined by the European Shortlist for Causes of Death (ESCD) by German state, sex, and five-year age groups. The ESCD harmonizes death counts before 1997 (International Classification of Diseases, Ninth Revision; ICD-9) and after 1998 (ICD-10). CHD was defined with the ESCD category for ‘ischemic heart diseases’, corresponding to I20-I25 (ICD-10) and 410–414 (ICD-9), thus also including acute myocardial infarctions. Stroke was defined using the ESCD ‘cerebrovascular diseases’ category, corresponding to I60-I69 (ICD-10) and 430–438 (ICD-9).

We have not included mortality data from years after 2019 due to a lack of availability at the time of analysis and to avoid potential biases in the projection of long-term CVD mortality trends arising from several mechanisms related to the COVID-19 pandemic. Key mechanisms are a higher uncertainty in death coding procedures during the pandemic [29]; elevated cause-specific mortality in vulnerable population subgroups which might have developed CVD in the future [30]; and the disruption of health services [31]. Since no post-pandemic mortality data is available, the inclusion of mortality data from the pandemic would likely lead to more unreliable long-term forecasts.

German states were classified into two East and West German sub-regions based on their historic geographic affiliation with the FRG (West Germany) and the former GDR (East Germany) [17]. Berlin, which was split in an Eastern and Western part during the time of the GDR, was excluded from all analyses to avoid potential biases (see Supplementary Methods).

2.2. Bayesian age-period-cohort model

We used a Bayesian age-period-cohort (BAPC) model to project mortality rates and the total number of deaths from CHD and stroke in people aged 30 and older in Germany from 2019 to 2035. All forecasts were implemented stratified by sex and separately for the former East and West German states (i.e., sub-regions) to allow for separate time trends. To calculate the projected number of deaths, we multiplied BAPC mortality rate projections with the official population projections. National forecasts were aggregated from the sub-regional forecasts. Methodological details of the implementation of the BAPC model with the *R* package *bamp* that we used have been extensively described elsewhere [32]. Similar methods were previously applied to forecast CVD mortality in England, Wales, the United States and Japan [33–35].

Briefly, in the BAPC the observed logit risk of death is modelled as a linear combination of the general mortality level (intercept) and age, period, and cohort effects [32]. Bayesian estimation is performed using Markov chain Monte Carlo sampling [36]. The forecast was directly applied to the observed number of deaths aggregated to five-year age groups for each sex, disease, and sub-region. Uncertainty in projected deaths was assessed with 80% and 95%-credible intervals (CrI). We assumed that uncertainty of the sub-region forecasts was uncorrelated when aggregating them to the national forecast. To improve readability and interpretation, the observed and projected number of deaths was aggregated to ten-year age groups for the reporting of results in tables.

The BAPC can handle both linear (i.e., second-order random walk) and constant time trends (i.e., first-order random walk) for the age, period, and cohort effects, with or without heterogeneity and overdispersion. This enables us to specify models according to several structures. To determine the best choice for each combination of sex, disease, and region, we projected the last 10-years of observed data (2010–2019) and selected best fitting model specification according to the mean absolute scaled error (MASE) [37]. A lower MASE indicates better predictive performance (Supplemental Table S1). All analyses were conducted in *R* (v4.2.2) with the package *bamp* (v2.1.3) [32,38]. Details are shown in the Supplementary Methods.

2.3. Comparison with alternative models

To validate our model choice, we projected the last ten years of observed data (i.e., 2010–2019) with Lee-Carter (LC) and functional demographic (FD) models in addition to the BAPC. The LC model is an established demographic time-series forecasting method, which is generalized by FD models using functional data analysis methods. Both models were implemented with the *R* package *demography* (v1.22) [26]. To compare the predictive performance of the three models we computed the MASE between the observed and projected total number of deaths by sex, disease, and region (Supplemental Table S1). Further details are described in the Supplementary Material.

2.4. Mortality decomposition

We followed Cheng et al. (2019) to decompose the difference in sex- and disease-specific total deaths between 1991 (i.e., reference year and population for the decomposition) and each subsequent observed or projected year into three components: Changes in population size, changes in the age structure (i.e., population ageing) and changes in age-specific mortality rates [39]. Beyond their main effects, this new method attributes all two- and three-way interactions between the components consistently and was shown to be more robust regarding the choice of the reference population compared to previous approaches [39].

2.5. Analysis of regional inequalities

To analyze mortality inequalities between East and West Germany over time, we computed the age- and sex-standardized number of deaths in East and West Germany for all observed and projected years (i.e., 1991 to 2035) using direct standardization to the 2019 national German population. Specifically, we estimated relative inequalities via yearly disease-specific SMRs by dividing standardized deaths in East Germany by those in West Germany. Uncertainty in SMRs was assessed using 95%-CIs which were calculated via published exact methods [40]. Absolute inequalities in 2019 and 2035 were calculated by computing the respective differences in standardized deaths. For consistency, we constructed the 95%-CIs for absolute inequalities based on the uncertainty of the SMRs. Details are presented in the Supplementary Methods.

3. Results

3.1. Observed CHD and stroke mortality trends from 1991 to 2019

On a national level, the crude number of deaths from CHD declined from 85,300 in 1991 (mortality rate: 386 per 100,000) to 64,000 in 2019 (mortality rate: 238 per 100,000) among men and from 87,300 (mortality rate: 343 per 100,000) to 50,600 (mortality rate: 176 per 100,000) among women (Table 1). Likewise, deaths from stroke declined from 38,100 in 1991 (mortality rate: 172 per 100,000) to 22,100 (mortality rate: 82 per 100,000) in 2019 among men and from 67,800 (mortality rate: 266 per 100,000) to 29,200 (mortality rate: 102 per 100,000) among women. The decline in crude mortality rates was more pronounced in the first half of this period from 1991 until 2005 (Table 1). This finding holds for CHD and stroke mortality rates in men and women across all age groups (Supplemental Figs. S9 and S10).

Over the whole period from 1991 to 2019 the crude CHD and stroke mortality rates for both men and women were higher in East compared to West Germany. For example, the CHD mortality rate in 1991 was 313 per 100,000 among women in West Germany, but 473 per 100,000 for their counterparts in the East. These differences have prevailed until 2019 and are consistent across age groups (Table 1, Supplemental Figs. S11-S14).

3.2. Projected CHD and stroke deaths from 2019 to 2035

Overall, we projected a further decline in CHD and stroke deaths from 2019 to 2035 in Germany for both sexes in all age groups except for 70- to 79-year-olds. The total number of projected deaths in 2035 was 103,500 [95%-credible interval: 81,700; 134,000] for CHD and 53,700 [41,400; 72,000] for stroke (Fig. 1, Table 2, Supplemental Table S9). For men, we projected a slight decrease in deaths from CHD from 2019 to 2035 by 3%, corresponding to a reduction of 2100 [−21,300; 18,000] deaths, but an increase in deaths from stroke of about 16% or 3600 [−4800; 18,300] deaths (Fig. 1, Table 2). For women, we projected a decrease in deaths from CHD and stroke of 20% (10,000 [−11,700; 23,000] fewer deaths) and 6% (1700 [−10,200; 9500] fewer deaths) from 2019 to 2035, respectively (Fig. 1, Table 2). We found that, on a national level, CHD and stroke mortality rates are likely to stagnate in most age groups from 2030 onwards for both men and women, thus continuing the slowdown observed between 1991 and 2019 (Supplemental Figs. S9 and S10). Due to population ageing this will lead to an inflection point around the year 2030 with rising CVD deaths thereafter (Fig. 1).

A comparison between projections in West and East Germany revealed that mortality trends are mostly consistent across the two subregions. The only exception is stroke mortality in East German men where slight declines (Change from 2019 to 2035: −790 [−3230; 8740]), as opposed to an increase in West Germany (Change from 2019

Table 1
Crude total number of cardiovascular deaths and crude mortality rate by sex and German region in 1991, 2005 and 2019.

	1991		2005		2019		1991–2019	
	Deaths	Mortality rate*	Deaths	Mortality rate*	Deaths	Mortality rate*	Deaths	
Germany							Difference	Change
Men								
CHD	85,300	386	69,900	276	64,000	238	−21,400	−25%
Stroke	38,100	172	24,200	95	22,100	82	−16,000	−42%
Women								
CHD	87,300	343	74,100	267	50,600	176	−36,600	−42%
Stroke	67,800	266	41,300	148	29,200	102	−38,600	−57%
West Germany								
Men								
CHD	65,600	363	55,000	263	49,900	223	−15,700	−24%
Stroke	28,700	158	19,200	92	17,900	80	−10,700	−37%
Women								
CHD	64,500	313	56,300	246	38,800	162	−25,700	−40%
Stroke	50,400	245	31,800	139	23,300	98	−27,100	−54%
East Germany								
Men								
CHD	19,800	490	15,000	339	14,100	311	−5700	−29%
Stroke	9500	235	5000	113	4200	93	−5300	−56%
Women								
CHD	22,800	473	17,800	364	11,900	246	−10,900	−48%
Stroke	17,400	360	9500	194	5900	121	−11,500	−66%

Legend: Absolute number of deaths rounded to hundreds and relative change rounded to the nearest integer. *Crude mortality rate per 100,000 persons. Abbreviations: CHD, coronary heart disease.

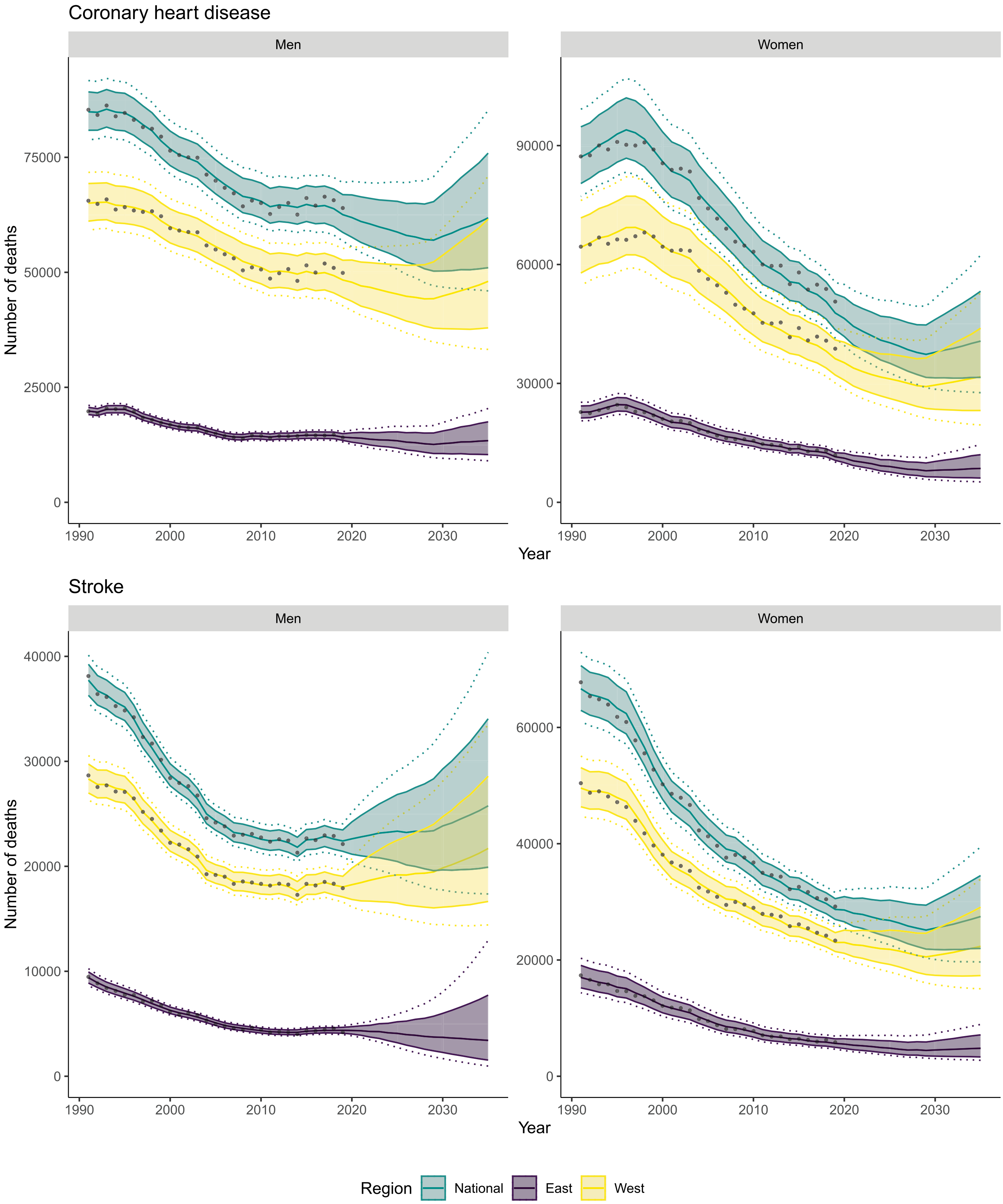

Fig. 1. Total number of observed and projected cardiovascular deaths in Germany by sex.
Legend: All panels – Total number of observed (black points) and projected cardiovascular deaths from the Bayesian Age-Period-Cohort model. Shaded areas indicate 80%-credible intervals. Dotted lines indicate 95%-credible intervals. National forecast is aggregated from sub-national estimates.

Table 2
Projected total number of cardiovascular deaths and absolute and relative change in Germany by sex from 2019 to 2035.

	2019	2035		2019–2035			
	Observed deaths	BAPC		BAPC		BAPC	
		Median	95%-CrI	Difference	95%-CrI	Change %	95%-CrI
Men							
CHD							
30–39	130	130	[80; 190]	−10	[−50; 50]	−5	[−37; 41]
40–49	810	720	[520; 1010]	−100	[−290; 190]	−12	[−36; 23]
50–59	3960	2220	[1660; 3110]	−1750	[−2310; −860]	−44	[−58; −22]
60–69	8910	7320	[5460; 10,300]	−1590	[−3450; 1390]	−18	[−39; 16]
70–79	15,420	20,900	[13,680; 32,240]	5480	[−1750; 16,820]	36	[−11; 109]
80+	34,750	30,170	[21,000; 44,550]	−4580	[−13,750; 9810]	−13	[−40; 28]
All ages	63,980	61,840	[45,960; 85,230]	−2140	[−18,020; 21,250]	−3	[−28; 33]
Stroke							
30–39	60	60	[40; 100]	0	[−20; 40]	3	[−39; 69]
40–49	230	250	[160; 390]	20	[−70; 160]	7	[−30; 68]
50–59	950	680	[450; 1070]	−270	[−490; 130]	−29	[−52; 13]
60–69	2480	2430	[1640; 3800]	−50	[−840; 1330]	−2	[−34; 54]
70–79	5770	7580	[4680; 12,630]	1810	[−1090; 6860]	31	[−19; 119]
80+	12,640	14,640	[9130; 24,550]	2000	[−3520; 11,900]	16	[−28; 94]
All ages	22,120	25,760	[17,370; 40,390]	3640	[−4760; 18,270]	16	[−21; 83]
Women							
CHD							
30–39	40	30	[20; 50]	−10	[−20; 10]	−22	[−59; 29]
40–49	160	170	[110; 250]	10	[−40; 100]	8	[−27; 61]
50–59	850	530	[380; 780]	−310	[−470; −70]	−37	[−56; −8]
60–69	2500	2370	[1690; 3480]	−130	[−810; 980]	−5	[−32; 39]
70–79	7010	9050	[5520; 15,320]	2050	[−1480; 8310]	29	[−21; 119]
80+	40,100	28,330	[18,290; 44,950]	−11,760	[−21,800; 4860]	−29	[−54; 12]
All ages	50,640	40,670	[27,650; 62,360]	−9970	[−22,990; 11,710]	−20	[−45; 23]
Stroke							
30–39	70	60	[30; 90]	−20	[−40; 20]	−21	[−53; 23]
40–49	160	170	[110; 240]	0	[−50; 80]	2	[−30; 46]
50–59	600	330	[240; 470]	−270	[−360; −130]	−45	[−60; −22]
60–69	1470	1250	[930; 1770]	−220	[−540; 310]	−15	[−37; 21]
70–79	4630	5830	[3840; 8890]	1200	[−790; 4260]	26	[−17; 92]
80+	22,270	19,750	[13,630; 29,190]	−2520	[−8640; 6920]	−11	[−39; 31]
All ages	29,200	27,470	[19,660; 39,430]	−1720	[−9540; 10,230]	−6	[−33; 35]

Legend: Absolute and relative change was computed from the difference between the total number of deaths in 2035 and in 2019. All numbers rounded to tens, except %-changes which are rounded to the nearest integer. Potential inconsistencies are due to rounding. Abbreviations: CHD, coronary heart disease; CrI, credible interval.

to 2035: 3780 [−3500; 15,570]), may be expected in the future. This finding is rooted in the underlying stroke mortality rates, which are projected to decline further among East German men but likely stagnate in most other strata (Supplemental Figs. S11-S14).

3.3. Mortality decomposition

Decomposing the past and projected number of CVD deaths, we find that in Germany for both sexes the past reduction (1991 to 2019) in deaths from CHD and stroke was driven by declines in age-specific mortality rates (Fig. 2, Supplemental Tables S10 and S11). However, population ageing, and population growth have partially mitigated this effect, particularly for men. According to our BAPC projections this trend will continue until around 2030 but is projected to reverse afterwards as the German population ages further and age-specific mortality rates continue to slow down and potentially stagnate (Fig. 2, Supplemental Tables S10 and S11). These findings are largely consistent for both East and West Germany, albeit population ageing is more important for the mortality dynamic in the East as the population size is projected to decrease (Supplemental Figs. S16 and S17, Supplemental Tables S10 and S11).

3.4. Regional inequalities

Age- and sex-standardized relative inequalities from CHD mortality have declined continuously from 1991 (SMR: 1.51 [1.40; 1.62]) to 2019 (SMR: 1.30 [1.14; 1.47]) (Fig. 3). However, our projections indicated no further reduction until 2035 (SMR: 1.30 [1.12; 1.50]). This may be explained by stagnating CHD mortality rates across age groups in both East and West Germany (Supplemental Figs. S11 and S13). In terms of absolute inequalities this results in a slight decrease from 33,700 excess deaths from CHD in East Germany in 2019 to 24,500 [9600; 41,100] in 2035 (Table 3).

For stroke there was likewise a rapid and consistent decline in age- and sex-standardized relative inequalities from 1991 (SMR: 1.57 [1.43; 1.72]) to 2019 (SMR: 1.07 [0.87; 1.31]) (Fig. 3). We projected inequalities from stroke mortality between East and West Germany to further decline until 2035 and potentially reverse (SMR in 2035: 0.85 [0.66; 1.08]). This is likely due to projected slightly decreasing mortality rates for some age-sex groups in the East, whereas mortality rates for their West German counterparts stagnate (Supplemental Figs. S12 and S15). This translates to a decrease from 3700 excess stroke deaths in East Germany in 2019 to 6800 [−3760; 15,600] excess stroke deaths in West Germany in 2035 (Table 3).

4. Discussion

From 1991 to 2019, CVD mortality rates in Germany have consistently declined for men and women across all age groups, albeit this decline has slowed or stopped in recent years particularly in East Germany. Likewise, despite population ageing, the total number of CVD deaths has also declined substantially among men and women across all age groups. Our BAPC projections from 2019 to 2035 indicate a further decline of CHD mortality in Germany by 10% (≈11,100 deaths). For stroke we project a slight increase in deaths of 5% (≈2400 deaths) driven by stagnating mortality rates in West German men. Decomposing

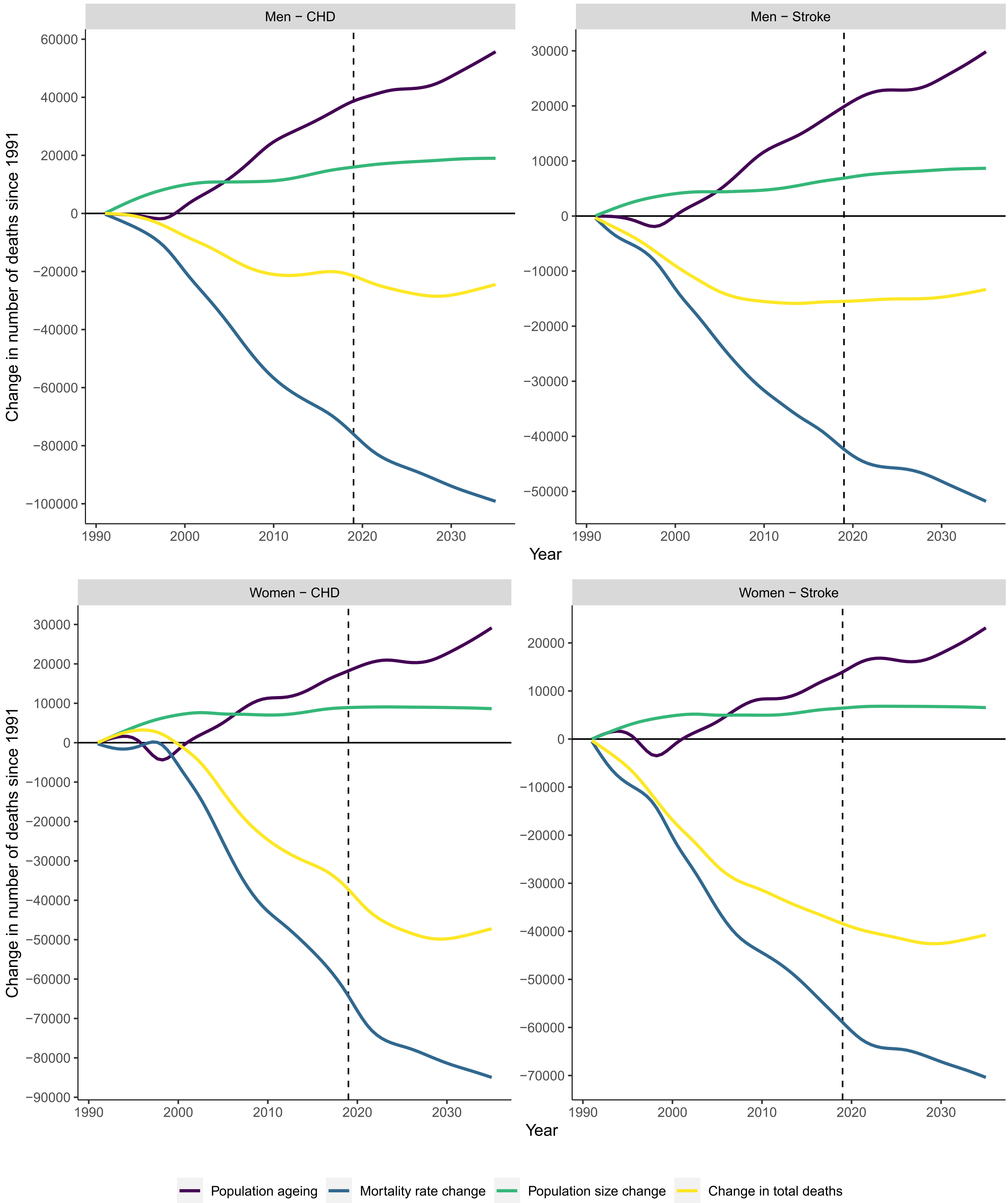

Fig. 2. Mortality decomposition of CHD and stroke in Germany by sex over time.
Legend: Smoothed version of original data using a generalized additive model. Solid lines: Observed change in deaths from 1991 to 2019 and projections from Bayesian age-period-cohort model from 2020 to 2035. Black lines: Total change in deaths over time. Red lines: Change of deaths due to population ageing. Green lines: Change of deaths due to population size. Blue lines: Change of deaths due to mortality rate.

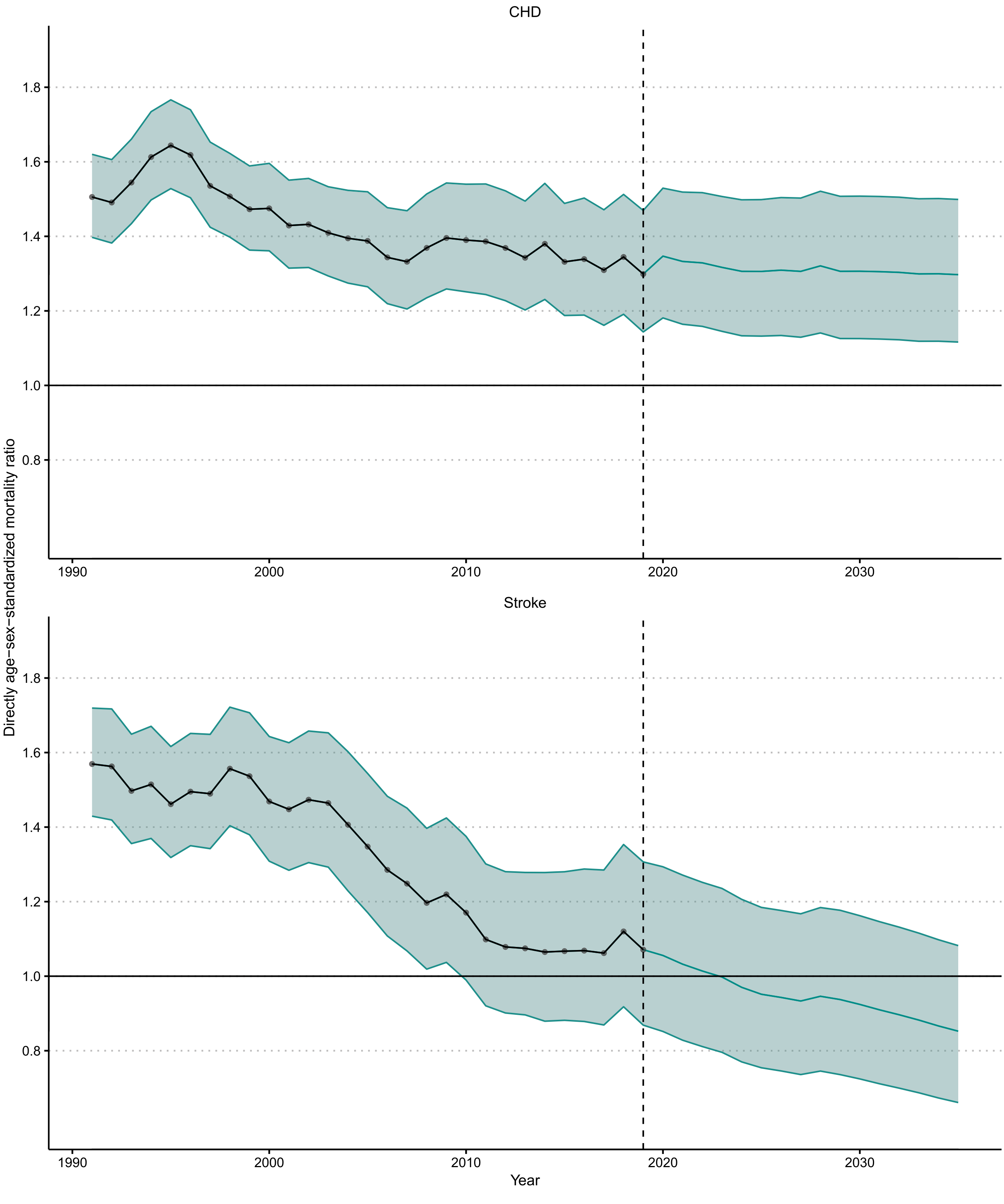

Fig. 3. Age-standardized mortality rate ratios of CHD and stroke between East and West Germany over time.
Legend: All panels – Observed (black) and projected (BAPC, turquoise) age-sex-standardized (Reference: 2019 German population) disease-specific mortality ratios (SMR) between East and West Germany from 1991 to 2035. Values >1 indicate higher mortality in East Germany. Vertical dashed line indicates begin of projection period in 2020. Shaded areas indicate 95%-confidence intervals.

the changes in national CVD mortality since 1991, we show that projected declines in mortality from CHD and stroke will likely partially be offset by the effects of population ageing and increases in population size. However, this trend is likely to slow down and reverse after around 2030. Using SMRs to analyze regional mortality inequalities between East and West Germany over time, we find that these have consistently declined from 1991 until 2019. Based on our projections for stroke, this trend will likely continue further, potentially even leading to higher age-sex-standardized stroke mortality in West Germany until 2035. However, mortality inequalities for CHD are projected to stabilize around

Table 3
Absolute inequalities of age-sex-standardized total number of deaths between East and West Germany in 2019 and 2035.

	2019	2035		2019–2035	
	Observed*	Mean*	95%-CI	Δ	95%-CI
CHD	33,740	24,450	[9570; 41,060]	−9290	[−24,170; 7310]
Stroke	3740	−6770	[−15,550; 3760]	−10,510	[−19,290; 20]

Legend: *Total number of age-sex-standardized deaths in East Germany - West Germany. All numbers rounded to tens. Abbreviations: CHD, coronary heart disease; CI, confidence interval.

2019 levels.

Two other studies have included Germany in their projections of the burden of cardiovascular disease. Wafa et al. (2020) projected the burden of stroke in Europe and estimated stroke deaths in Germany to decline to 35,000 by 2047, which implies a large reduction and is not consistent with our analysis [41]. These differences are likely related to different forecasting methods. Wafa et al. (2020) used a regression-based approach to forecast mortality based on time and GDP, which does not take explicit age, period, and cohort effects into account. Similarly, as part of the Global Burden of Diseases, Injuries, and Risk Factors Study 2016, an analysis using a component model of cause-specific mortality projected stroke deaths in Germany in 2040 to decrease to 43,000 in the reference and 56,000 in the pessimistic scenario. However, the same analysis, while also projecting a decline in CHD deaths in the reference scenario, reported an about twofold higher absolute number of deaths in 2016 and 2040, which is potentially related to diverging case definitions [42].

Based on the observed CVD mortality from 1991 to 2019 we provide further evidence on recent trends that others have described for Germany and generally for the USA, UK, and other European countries. Namely a slowing decline or stagnation of mortality rates for CHD and stroke, which might be responsible for slowing improvements in life expectancy [6–9,11,12,15,17,43]. The impact on the future CVD mortality burden of a continuation of these trends can be deduced from our projections. Using a Bayesian approach which incorporates age, period, and cohort effects we account for these recent shifts and project further stagnating mortality rates (Supplemental Figs. S9-S14). In our mortality decomposition analysis, we show that these trends together with the effect of population ageing will likely lead to an increase in the number of cardiovascular deaths after 2030 (Fig. 2). This is consistent with previous global projections and analyses from the US and the UK [2,33,34,44].

The underlying mechanisms of the observed shift in CVD mortality since 2010 have yet to be illuminated but are likely related to an increasing prevalence of diabetes, obesity, and unhealthy lifestyles, such as smoking, physical inactivity and diets consisting of large amounts of ultra-processed foods. Already implemented clinical prevention and treatment approaches might also have exploited their full potential and provide diminishing returns [3–5]. The most recent German risk factor surveillance data shows a moderate decline in smoking prevalence among men and women since the mid-2000's, consistent decreases in physical inactivity since the late 1990's but consistent increases in obesity, particularly among younger age groups [45–47]. Additionally, studies suggest that the prevalence of obesity, diabetes, and CVD in Germany is likely to increase over the coming decades [48–52]. Considering these trends together with recently observed mortality trajectories in Germany, the stagnation of CVD mortality rates and prospective increase in deaths, as projected in our study, seems plausible.

It must be acknowledged that future trajectories of CVD mortality could be affected by the COVID-19 pandemic due to several mechanisms. First, at the beginning of the pandemic, cause of death definitions were less reliable since coding procedures were not established [29]. Second, all-cause and cause-specific mortality was elevated compared to a historical baseline as COVID-19 affected primarily frail populations at a very high age and other vulnerable groups with specific risk factor profiles, such as patients with respiratory diseases or suppressed immune systems, some of which would have developed CVD in the future [30]. Third, in most healthcare systems services were interrupted which led to delayed diagnosis and treatment in routine care [31].

The potential direction, degree, and persistence of these effects on future CVD mortality is likely complex. Inclusion of mortality data from the COVID-19 pandemic could have led to an underestimation of future CVD mortality trends because some of the expected future deaths will not happen. However, this period effect might be independent of long-term mortality trajectories as these are largely determined by behavioral factors, socio-economic circumstances, and healthcare access [5]. To avoid potentially resulting biases, we have thus excluded mortality data from the years after 2019 in our projections. Future studies could use these projections to evaluate the impact of the COVID-19 pandemic on long-term CVD mortality trends once a substantial amount of post-pandemic mortality data has accrued.

Although health-related inequalities and the convergence of all-cause and disease-specific mortality between East and West Germany have been under scrutiny by researchers over the last decades, no projections like the ones presented in this study exist. Others analyzed sex and disease-specific pre- and post-reunification mortality trends [17,19,22–24,43,53], discussed the underlying potential economic, socio-cultural, and healthcare-related mechanisms of mortality convergence [17,54], estimated the impact of age selection [55] and discussed the impact of changes in East German smoking prevalence on future mortality in women of specific age groups [20].

We show that, if recent mortality trends continue, future mortality convergence (according to age-sex-standardized SMRs; Fig. 3) is unlikely for CHD, but possible for stroke due to projected further decreasing mortality rates among East German men. Because long-term trends in regional mortality inequalities are related to underlying risk factor trajectories, they can be complex to analyze and understand. For example, Vogt et al. (2017) predicted that a great increase in smoking prevalence among East German women in the decade after the reunification will likely lead to a future lung cancer mortality divergence between East and West [20]. However, while smoking will impact lung cancer incidence and mortality decades later, effects on cardiovascular disease are more immediate [56]. To what degree, which risk factors might be responsible for regional health inequalities should thus be carefully analyzed in future studies.

Our projections highlight the importance for a close monitoring of cardiovascular and diabetes prevalence, incidence, and mortality trends in Germany to better understand implications for health policy and priority setting. The continuous surveillance of key related risk factors is equally important to attribute trends in disease epidemiology to their underlying causes and potentially identify unknown factors [57,58]. Consistently collecting this data across regions and socioeconomic subpopulations is further key to understand health inequalities but not common in publicly available official German mortality data.

Granular epidemiological surveillance is also essential for the design and implementation of effective population-based preventive policies. Our results support the need for a comprehensive approach to strengthen existing NCD prevention efforts [57]. Moreover, risk reductions from population-level interventions can be expected even within few years [56]. Germany is among the countries with the highest prevalence of smoking in Europe and scores 5th worst on the Tobacco Control Scale, which indicates national-level implementation of tobacco control policies, out of the EU27 countries [59]. Additionally, Germany lacks implementation of key evidence-based nutrition policies to prevent obesity and other detrimental effects of unhealthy diets [60].

5. Strengths and limitations

Our study has several strengths. We used recent official data on death counts and population count projections and implemented published adjustments for intercensal projections for population counts before 2011 [28]. Our application of a Bayesian forecasting method, calibration, extensive validation, and model comparison procedures leads to robust results. The analysis of the mortality dynamic in Germany including mortality inequalities between East and West supports health policy priority setting. Finally, the produced forecasts can be used in future applications of population health modelling in Germany.

Limitations of our approach include that the applied method does not explicitly account for changing population-level risk factor, treatment, and prevention patterns over time. Yet, it is reasonable to assume that these long-term trends and effects are implicitly included in the morality time series. As discussed, our approach also does not enable us to model any future disruptions, including the COVID-19 pandemic or economic crises. Although the short-term detrimental cardiovascular effects of COVID-19 are well documented [61–63], multiple years of post-pandemic mortality data would be needed to assess whether the COVID-19 pandemic induced long-term changes in mortality. Additionally, long-term mortality trends are largely determined by behavioral factors, socio-economic circumstances, and healthcare access [5]. Our Bayesian framework, in which we model cause-specific mortality independently, is also unable to incorporate competing risks between stroke and CHD. This is a well-known problem in cause-specific mortality forecasting, particularly if the objective is to coherently aggregate cause-specific estimates to all-cause mortality forecasts. However, it can be argued that the impact of historical changes in non-CHD (or stroke) mortality are implicitly incorporated in the historic CHD (or stroke) mortality and population count time series. Thus, we expect the resulting bias for our projections to be small and likely much smaller than the estimated uncertainty intervals as we do not aggregate cause-specific mortalities and analyze only two causes. In our analysis of East-West mortality convergence we are further unable to explicitly account for migration between the two regions. However, migration is implicitly included in the official population projections and others have argued that this intra-national migration had a negligible effect on mortality differences in the past [17,53]. Beyond the historic geographic division in East and West Germany, researchers have focused on more granular mortality differences within states and between urban and rural areas in Germany [64]. Due to the limited granularity of publicly available official death counts we were unfortunately not able to address these questions. Importantly, we must rely on the accuracy of cause-of-death definitions in these death counts. Although the German health reporting system has detailed procedures for documentation and reporting, a major limitation of using this data for mortality estimation is that multiple causes cannot be distinguished.

6. Conclusions

We provide evidence that the CVD mortality decline in Germany has slowed in a similar way to other high-income countries. Using Bayesian methods, which take age, period, and cohort effects into account, we show that the total number of deaths from CVD is likely to decline further, offsetting population ageing. However, this trend is potentially reversed after 2030 based on whether CVD mortality rates will continue to stagnate or resume to decline; the former being consistent with current trends in key determinants of CVD risk such as obesity, diabetes, and smoking. This also has profound implications for East-West CHD mortality inequalities in Germany, which are not projected to decrease further. CVD risk factors should be carefully analyzed and addressed by comprehensive public health policy action for which Germany has much opportunity.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Data sharing statement

No primary data was collected for this study. The datasets used and/or analyzed during the current study are available from the corresponding author after publication of this study upon reasonable request.

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The funding source had no influence on the design of the study; the collection, analysis, or interpretation of the data; the writing and editing of the manuscript; and the decision to submit the paper for publication.

Authors' contributions

K.M.F.E.-F., S.L., M.F, C.K. and M.L. drafted and critically revised the concept and methods of the study. K.M.F.E.-F. and S.L. had direct access to the data, performed data preparation, implemented the analysis, and verified the underlying data reported in the manuscript. K.M.F.E.-F. constructed the figures and tables. K.M.F.E.-F., S.L., M.F., C.K. and M. L. were responsible for the interpretation of the data. K.M.F.E.-F. and C. K. prepared the initial manuscript draft. S.L., M.F. and M.L. substantially revised the initial draft. All authors reviewed, edited, and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijcard.2023.131359.

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2. Interim Evaluation of Germany's Sugar Reduction Strategy for Soft Drinks: Commitments versus Actual Trends in Sugar Content and Sugar Sales from Soft Drinks

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Interim Evaluation of Germany's Sugar Reduction Strategy for Soft Drinks: Commitments versus Actual Trends in Sugar Content and Sugar Sales from Soft Drinks

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Keywords
Soft drinks · Sugar intake · Obesity · Germany · United Kingdom

Abstract
Introduction: A high intake of sugar, in particular from sugar-sweetened soft drinks, increases the risk for obesity, type 2 diabetes mellitus, and dental caries. Germany has pursued a national strategy for sugar reduction in soft drinks based on voluntary commitments by industry since 2015, but its effects are unclear. ***Methods:*** We use aggregated annual sales data from Euromonitor International to assess trends in mean sales-weighted sugar content of soft drinks and per capita sugar sales from soft drinks in Germany from 2015 to 2021. We compare these trends to the reduction path set by Germany's national sugar reduction strategy and to data for the United Kingdom, which adopted a soft drinks tax in 2017 and which we selected as best practice comparison country based on pre-defined criteria. ***Results:*** Between 2015 and 2021, the mean sales-weighted sugar content of soft drinks sold in Germany decreased by 2% from 5.3 to 5.2 g/100 mL, falling short of an interim 9% reduction target and a 29% reduction observed in the United Kingdom over the same period. Sugar sales from soft drinks in Germany decreased from 22.4 to 21.6 g/capita/day (–4%) between 2015 and 2021 but remain high from a public health perspective. ***Conclusions:*** Reductions observed under Germany's sugar reduction strategy fall short of stated targets and trends observed internationally under best practice conditions. Additional policy measures may be needed to support sugar reduction in soft drinks in Germany.

Introduction

An increasing body of evidence links excess consumption of free sugars with a number of adverse health outcomes [1, 2]. Sugar intake from beverages is of particular

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concern [2]. Evidence from randomized controlled trials and observational studies shows that sugar-sweetened beverages can contribute to weight gain and an increased risk for overweight and obesity [3–5], while observational studies show positive associations with an increased risk for diabetes mellitus type 2, dental caries, and overall mortality [6–8]. Sugar-sweetened soft drinks are, therefore, considered an important driver of the global epidemic of obesity, type 2 diabetes mellitus, and other chronic diet-related diseases [9, 10].

The World Health Organization (WHO), therefore, recommends to limit intake of free sugars among adults and children to no more than 10% of total energy intake, noting that additional health benefits may be achieved by limiting it to no more than 5% [2]. Similarly, the European Food Safety Authority (EFSA) concludes that due to the observed health risks, no safe upper level of intake can be set for added and free sugars, and that intake should be as low as possible in the context of a nutritionally adequate diet [11]. The German guidelines on sugar intake follow the WHO in recommending to limit intake of free sugars to less than 10% of total energy intake, or approximately 50 g/day for an average adult with a total energy intake of 2,000 kcal/day [12]. Current sugar intake levels in Germany are estimated to range from 13% to 19% of total energy intake, depending on gender and age [12].

Sugar reduction in soft drinks is also a declared policy objective of the German government. As its landmark nutrition policy act, it announced in 2015 a National Strategy for the Reduction of Sugar, Fat, and Salt in Processed Foods [13]. In the subsequent years, specific reduction targets were defined through formal agreements between the government and food industry groups, including a commitment to reduce the average sugar content of soft drinks sold in Germany by 15% between 2015 and 2025 [14–16]. In 2022, the newly elected German government announced that if the prior approach based on voluntary commitments by the food industry proved insufficient, additional measures (including a tax on sugar-sweetened beverages) would be considered as part of a new national nutrition strategy to be developed until the end of 2023 [17, 18].

Against this backdrop, the present paper evaluates Germany's current sugar reduction strategy for soft drinks by assessing trends in mean sales-weighted sugar content of soft drinks and per capita sugar sales from soft drinks from 2011 to 2021. We compare these trends with the reduction path set by Germany's national sugar reduction strategy, and with data for the United Kingdom (UK), which adopted a soft drinks tax in line with international recommendations in 2017, and which we selected as best practice comparison country based on pre-defined criteria.

Methods

Study Design and Setting

This is a policy evaluation based on a repeat cross-sectional analysis of aggregated annual sales and ingredient data provided by Euromonitor International, a market research company. The evaluation is based on three comparisons: actual trends versus reduction targets; actual trends in Germany versus trends in the UK; and actual trends before and after Germany's sugar reduction strategy was announced. We chose the UK as international best practice comparison country based on the following pre-defined criteria: geographical proximity and similarity in market size to Germany; and implementation of a soft drinks tax aligned with WHO recommendations (including the use of a tiered tax design to incentivize reformulation) [19]. A detailed description of our methodological approach, including the steps taken to select the comparison country, is provided in the online supplementary material (see www.karger.com/doi/10.1159/000529592 for all online suppl. material). Our study follows the STROBE reporting guideline [20].

Variables

We assess the mean sales-weighted sugar content of soft drinks, the mean amount of sugar sold through soft drinks per capita per day, and mean soft drinks sales per capita and day. In line with common usage, we define soft drinks as non-alcoholic, non-dairy beverages with added sweeteners (including sugar and other caloric sweeteners, as well as high-intensity, non-nutritive sweeteners such as aspartame) [21]. Our definition of soft drinks, therefore, includes varieties with sugar as well as sugar- and calorie-free varieties sweetened with non-nutritive sweeteners. Sugar is defined in line with the EFSA definition of added sugars [11].

Data Sources and Methods of Assessment

We use data from the Euromonitor Passport database collected and provided by Euromonitor International. Euromonitor provides sales and ingredient data based on primary and secondary data sources, including company reports, official statistics, store audits, product information (such as ingredient and nutrient declarations), interviews with companies, and estimates by in-house experts [22]. The Euromonitor Passport database is considered to be one of the most comprehensive and reliable sources for such data and has been used extensively in public health research, including studies on soft drinks sales and composition [23–25]. For soft drinks, the database covers both off-trade sales (i.e., sales through retail outlets) and on-trade sales (i.e., through hospitality and catering outlets). Euromonitor uses an internationally standardized methodology, which allows for comparisons between countries and over time [22].

We obtained sales and ingredient data for all beverage categories meeting our definition of soft drinks, i.e., carbonates (including cola carbonates, lemonade and lime, ginger ale, tonic water and other bitters, orange carbonates, and other non-cola carbonates), juice drinks (with up to 24% juice), nectars (with more than 24%

but less than 100% fruit), flavoured bottled water, functional bottled water, energy drinks, sports drinks, and ready-to-drink tea. We included powder and liquid concentrates in our calculation of per capita sugar sales from soft drinks but not in the calculation of the mean sales-weighted sugar content and per capita soft drink sales. We aggregated data for the beverage and ingredient categories included in our definition of soft drinks and free sugars, respectively, as listed in the online supplementary material. For information on Germany's sugar reduction strategy, we used official government publications [13, 15, 16, 26].

Analysis

We descriptively plot the annual mean sales-weighted sugar content of soft drinks and per capita sugar sales from soft drink sales from 2011 to 2021. To compare this trend to the targets of Germany's national sugar reduction strategy, we calculated a linear reduction path based on the observed value for the strategy's baseline year (2015) and the relative reduction target set by the strategy for 2025 (the strategy does not define interim targets but emphasizes that its reduction targets will be achieved stepwise and gradually, justifying the assumption of a linear reduction path [14, 15]). We then compare outcome trends in Germany to those over the same period in the UK. Finally, we compare outcome trends in Germany before and after 2015. For this last comparison, we calculate the compound annual reduction rate in the mean sales-weighted sugar content of soft drinks in Germany for 2011–2015 and 2015–2021, respectively.

We use 2015 as the baseline for our analysis, as this is the baseline year to which the sugar reduction targets, as stated in government and industry publications, refer [14, 15]. 2015 is also the year in which the sugar reduction strategy was first publicly announced, even though the specific reduction targets for soft drinks were published only in 2019 (according to industry sources, the earlier baseline year of 2015 was chosen to account for sugar reductions achieved in the preceding years, i.e., between the first announcement of the strategy in 2015 and the publication on the 15% reduction target in 2019) [14]. We also report data for 2011–2014 to allow for a comparison of trends before and after the strategy's baseline year. We chose 2011–2021 as the overall time frame of our analysis as this was the time span for which comparable data were available from Euromonitor when we conducted our analyses.

Study Registration and Protocol Availability

A protocol for this study was developed and prospectively registered with the Open Science Framework (registration DOI 10.17605/OSF.IO/3WJ49) before data were analysed [27]. Differences between protocol and manuscript are explained in the online supplementary material.

Results

Trends in Sugar Content of Soft Drinks in Germany

The mean sales-weighted sugar content of soft drinks sold in Germany decreased between 2011 and 2021 (from 5.4 g/100 mL to 5.2 g/100 mL, −3%), as did mean per capita sugar sales from soft drinks (from 24 g/capita/day

Table 1. Mean sales-weighted sugar content of soft drinks, soft drink sales, and sugar sales from soft drinks, Germany and the UK, 2011–2021

Country	Measure	Unit	2011	2012	2013	2014	2015*	2016**	2017	2018***	2019	2020	2021	Change 2011–2021	Change 2015–2021
Germany	Mean sales-weighted sugar content of soft drinks (excluding concentrates)	g/100 mL	5.4	5.3	5.3	5.3	5.3	5.3	5.3	5.2	5.2	5.2	5.2	**−3.2%**	**−2.2%**
Germany	Total sugar sales through soft drinks (including concentrates)	g/capita/day	24.0	23.8	23.4	22.9	22.4	22.1	21.7	22.1	21.9	21.0	21.6	**−9.9%**	**−3.6%**
Germany	Total soft drink sales (excluding concentrates)	mL/capita/day	428	426	422	412	404	401	395	402	398	383	389	**−9.0%**	**−3.6%**
UK	Mean sales-weighted sugar content of soft drinks (excluding concentrates)	g/100 mL	5.6	5.5	5.5	5.5	5.3	5.1	4.6	4.0	3.9	3.7	3.8	**−32.2%**	**−28.7%**
UK	Total sugar sales through soft drinks (including concentrates)	g/capita/day	22.6	22.4	22.3	21.9	21.2	20.2	18.8	15.6	15.6	15.3	15.1	**−32.9%**	**−28.5%**
UK	Total soft drink sales (excluding concentrates)	mL/capita/day	289	288	289	288	288	286	293	293	300	293	290	**0.2%**	**0.7%**

Data sources: Own calculations based on data from Euromonitor International (Passport database). UK, United Kingdom; SDIL, Sugary Drinks Industry Levy. * Baseline year of the reduction targets of Germany's national sugar reduction strategy for soft drinks. ** Year of the announcement of the Sugary Drinks Industry Levy (SDIL) in the UK. *** Year when the SDIL took effect in the UK.

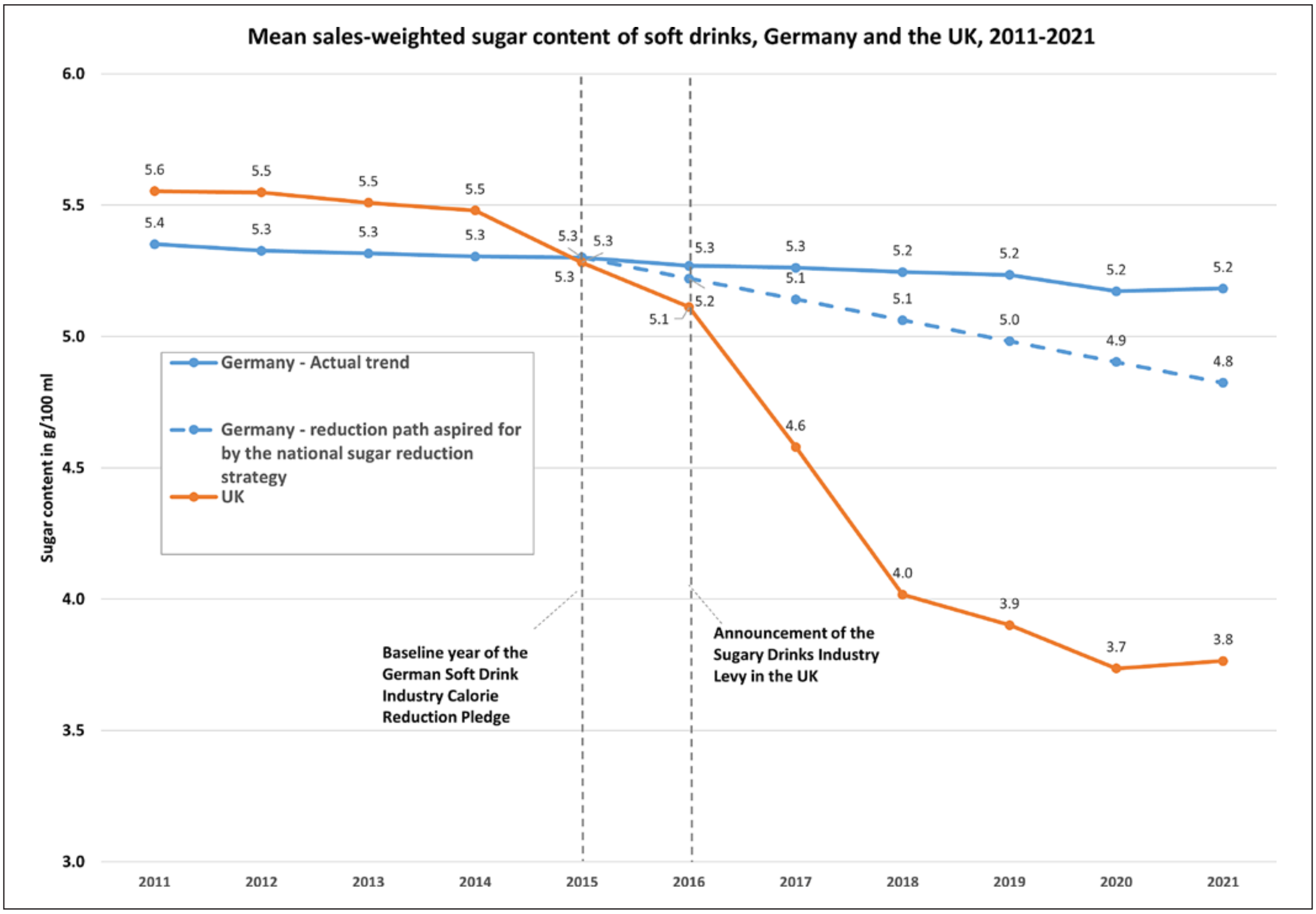

Fig. 1. Mean sales-weighted sugar content of soft drinks in Germany and the UK, 2011–2021 in g/100 mL (solid lines), as well as the reduction path set by Germany's national sugar reduction strategy (dashed line). Data sources: Own calculations based on data from Euromonitor International and Germany's Federal Ministry of Food and Agriculture [16].

to 22 g/capita/day, –10%) and mean soft drinks sales per capita (from 428 mL/capita/day to 389 mL/capita/day, –9%) (see Table 1; Fig. 1–3).

Comparison of Actual Trends in Germany with Reduction Targets and with Trends in the UK

During the time period covered by Germany's national sugar reduction strategy for which data were available (2015–2021), the mean sales-weighted sugar content of soft drinks sold in Germany decreased by 2% (from 5.3 g/100 mL to 5.2 g/100 mL). This contrasts with a 9% interim reduction target for the same time period implied by the sugar reduction strategy, as well as with a 29% reduction (from 5.3 g/100 mL in 2015 to 3.8 g/100 mL in 2021) observed in the UK (see Fig. 1). Sugar sales from soft drinks decreased in the UK in this time period from 21 g/capita/day in 2015 to 15 g/capita/day in 2021 (–28%), while total soft drink sales increased slightly from 288 to 290 mL/capita/day (+1%) (see Table 1).

Comparison of Pre- and Post-Pledge Trends

The compound annual reduction rate of the mean sales-weighted sugar content of soft drinks in Germany during the 4 years prior to the baseline of the sugar reduction strategy (2011–2015) was 0.2% and increased slightly to 0.4% during the years covered by the strategy for which data were available (2015–2021).

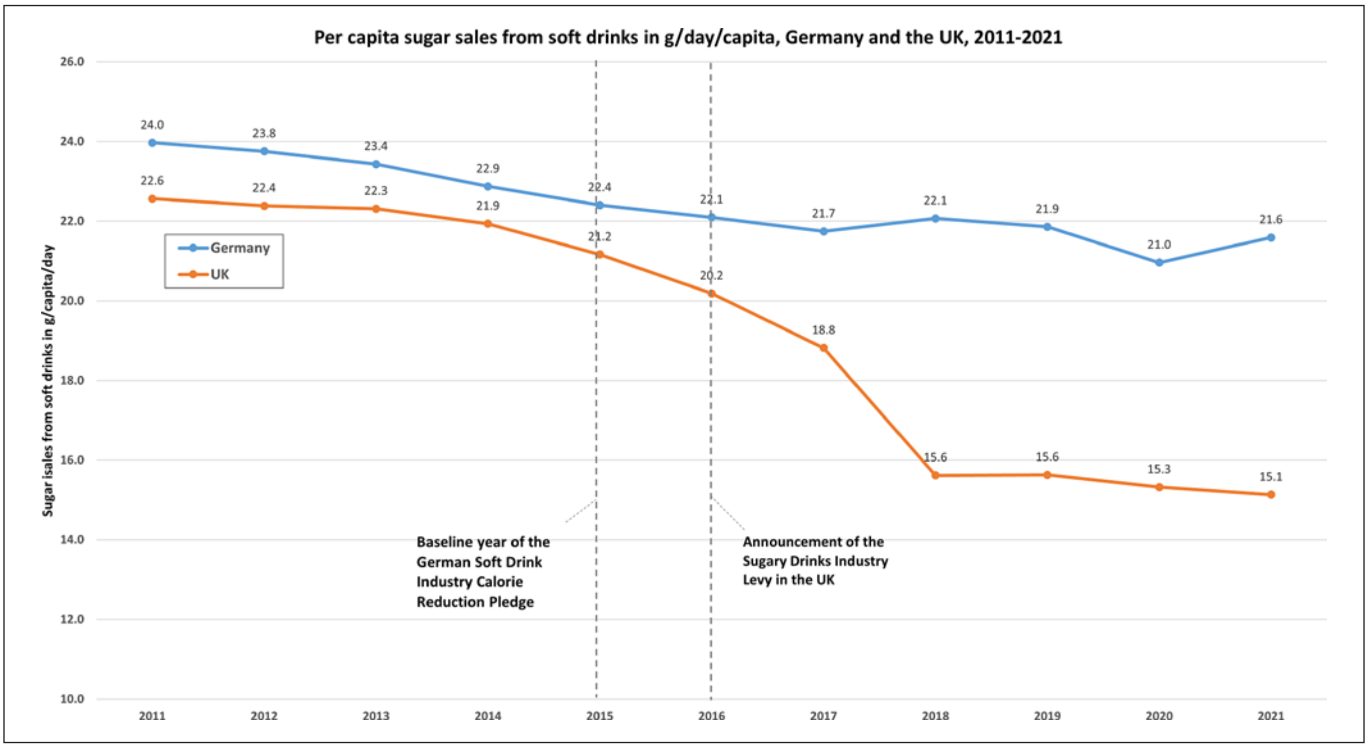

Fig. 2. Mean sugar sales from soft drinks per capita in Germany and the UK, 2011–2021 in g/d/capita. Data sources: Own calculations based on data from Euromonitor International (Passport database).

Discussion

Key Findings and Public Health Implications

During the time period covered by Germany's current national sugar reduction strategy for which data were available (2015–2021), the mean sales-weighted sugar content of soft drinks sold in Germany decreased only slightly by 2%, which falls short of an interim 9% reduction target, as well as of the 29% reduction achieved in the UK during the same time period. At the current pace, Germany is, therefore, not on track for meeting the 15% reduction target it has set itself for 2025, which is modest compared to the reductions achieved in the UK to date. The average annual reduction rate increased slightly after the strategy was announced in 2015, from 0.2% per year in 2011–2015 to 0.4% per year in 2015–2021.

Per capita sugar sales from soft drinks in Germany decreased by 4% since the national sugar reduction strategy was first announced in 2015 but still stood at 22 g/day/capita in 2021. For an average adult with a daily energy requirement of 2,000 kcal/day, this corresponds to almost half the recommended maximum intake of free sugars (10% of total energy intake or 50 g/day) [2, 12]. Dietary surveys show that soft drink intake is highly unevenly distributed in the population, with children, teenagers, and young adults consuming two to three times more than older adults, and low socioeconomic status groups consuming more than high socioeconomic status groups [28, 29]. This suggests that young people and socioeconomically disadvantaged groups in Germany may exceed the recommended maximum intake of free sugars through their soft drink intake alone. This underlines the importance of reducing sugar intake from soft drinks.

Soft drinks sales per capita in Germany decreased during that same time period by 3.6% (from 404 mL/capita/day in 2015 to 389 mL/capita/day in 2021) but remain higher than recommended (due to their demonstrated adverse health effects, dietary guidelines generally do not define a safe upper limit for soft drinks, but recommend to avoid or limit their intake [30, 31]). Soft drink sales per capita slightly increased in the UK (from 288 mL/capita/day in 2015 to 290 mL/capita/day in 2021, +0.7%), suggesting that substantial sugar reductions do not necessarily result in lower total sales of soft drinks.

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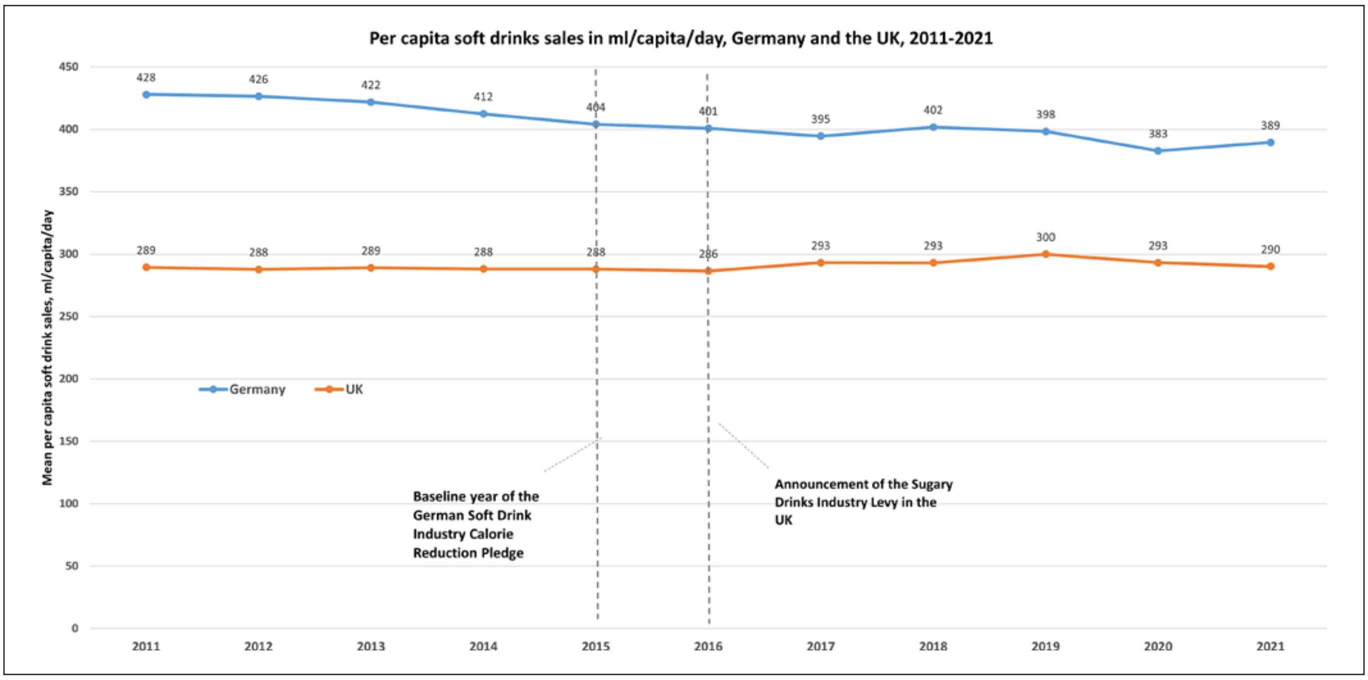

Fig. 3. Mean soft drink sales per capita in Germany and the UK, 2011–2021 in mL/day/capita. Data sources: Own calculations based on data from Euromonitor International (Passport database).

Strengths and Limitations

To the best of our knowledge, our study is the most comprehensive assessment to date of recent trends in sugar content, sales, and sugar sales from soft drinks in Germany. The only publicly available recent assessments we are aware of were limited to comparisons between single years (2016 and 2018, and 2018 and 2019, respectively), did not cover soft drink sales in the hospitality sector, were based on non-representative samples, and were not sales-weighted [32–34]. The Euromonitor Passport Database used for our analysis provides a comprehensive market coverage and is based on a standardised methodology, which allows for comparisons between countries and across time [22]. Our analysis is based on sales and ingredient data, which are, unlike self-reported dietary survey data, not prone to recall and social desirability bias. Finally, we defined key aspects of our methodology in an a priori protocol developed and published before data were analysed [27].

Our study also has a number of limitations. While sales figures can be considered reasonable proxies for consumption and may be more reliable than self-reported dietary intake data, they do not account for food waste of the final consumer (i.e., drinks left over or discarded by consumers). Besides, we did not include liquid and powder concentrates (which are diluted by the final consumer before consumption) in our estimates for soft drink sales volumes and mean sugar content, as dilution ratios may vary. We calculated sugar content based on the use of sugar as ingredient, but were unable to account for the sugar content of fruit juices used as ingredient in some types of soft drinks (such as nectars). Due to data limitations, we were also unable to differentiate between regular and low-calorie soft drinks, and we did not assess trends in the use of high-intensity sweeteners. We were also unable to assess trends for sub-populations (such as children), as our data represents population-wide averages. Moreover, while Euromonitor is generally considered a reliable source of sales and ingredient data, its data are partially based on estimates by its technical and industry experts, and reported outcomes may, therefore, be different from the true values [22]. Due to data limitations we were unable to quantify this uncertainty. Finally, our analysis is descriptive, and we did not attempt to establish causal relationships between the observed trends and factors that may have influenced them. In particular, reductions seen in average sugar sales from soft drinks in Germany between 2015 and 2021 may reflect secular trends, rather than effects of the sugar reduction strategy. Of note, dietary survey data from the DONALD study suggest that among children and adolescents in Germany sugar intake from soft drinks decreased between 1985 and 2016 [35].

Comparisons with Other Studies

Data on the sugar content of soft drinks, and sugar sales from soft drinks in Germany is limited. Following a mandate by Germany's Federal Ministry of Food and Agriculture (BMEL), the Federal Research Institute for Nutrition and Food (Max-Rubner-Institut, or MRI) published two reports on the sugar content of soft drinks on the German market in 2018 and 2020 [34, 36]. The second and more comprehensive of these reports, published as an updated version in June 2020, reports data for two main beverage categories: soft drinks ("Erfrischungsgetränke" in German) as well as sugar-sweetened beverages ("gesüßte Erfrischungsgetränke" in German, including soft drinks with caloric sweeteners but excluding soft drinks sweetened exclusively with non-nutritive sweeteners) [36]. Data for specific sub-categories (such as lemonades) are also reported. Data collection covered beverages sold through retail outlets, and followed a stepwise process including online research on manufacturers' websites, enquiries with manufacturers as well as on-site research in grocery stores. Results are not weighted by sales, but for the follow-up assessment in 2019, data on the mean sugar content are presented separately for the full range of products included in the analysis, and for top-selling products identified through household panel data from the market research company GfK. For the full range of soft drinks, the median sugar content is reported as 6.2 g/100 mL in 2018, and 6.0 g/100 mL in 2019, a relative decrease of 3.2% [36]. For sugar-sweetened beverages, the median sugar content of the full product range is reported as 6.5 g/100 mL in 2018 and 6.2 g/100 mL in 2019, a relative decrease of 4.6% [36]. For top-selling products, the median sugar content for sugar-sweetened beverages is reported as 5.9 g/100 mL in 2019. In our analysis, we found the average sales-weighted sugar content of soft drinks to be 5.25 g/100 mL in 2018 and 5.23 g/100 mL in 2019, a relative decrease of 0.20%. Our figures, therefore, show a lower absolute level of sugar content for both years, and a smaller relative decrease between the 2 years. These differences may be explained by the fact that our figures are weighted by sales, include the hospitality sector, and are based on a slightly different definition of soft drinks (the MRI data set did not include nectars) and on a different data source (Euromonitor data vs. the MRI's own sample of beverages). A comparison of our results with further studies (including studies from the UK) is provided in the online supplementary material.

Policy Implications

So far, the approach pursued by the German government to reduce sugar intake from soft drinks and average sugar content of soft drinks sold in Germany has not fully achieved its stated objectives. This suggests that additional policy measures may be needed. In 2020, the Scientific Advisory Council at Germany's Federal Ministry of Food and Agriculture (WBAE) proposed a number of measures to reduce the adverse health effects of soft drink consumption in Germany, including a levy on sugar-sweetened beverages proportional to their content of free sugars [37]. Besides its intended effects on sales and consumption of sugar, this could generate revenue of 1.0–1.9 billion € annually, which could be used to partially fund a value added tax exemption for healthy foods including fruit and vegetables [37]. This proposal has received renewed attention in light of recent increases in the price of staple foods, as well as due to its potential environmental co-benefits [38]. Similar to the Sugary Drinks Industry Levy in the UK, revenue could also be used to fund free, healthy school meals [37]. Further measures recommended by the WBAE include improvements to the availability of healthy beverages in schools, kindergartens, hospitals, and other public settings and an action plan for the promotion of drinking water (including a mandate that free drinking water must be available for consumption in all foodservice establishments) [37]. These recommendations are in line with a report of Germany's national nutrition research institute (the Max-Rubner-Institute), which concluded in 2016 that regulatory and fiscal measures should be considered if the industry's voluntary reformulation commitments proved insufficiently effective [39]. Additional measures recommended by the institute include improved nutrition labelling and the regulation of marketing of food with a high content of sugar [39]. In light of the findings of the present study, and the well-established adverse health effects of sugar-sweetened soft drinks, these measures should be considered as part of the new national nutrition strategy announced for 2023 [18].

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Statement of Ethics

No human subjects were involved in this research, and no ethical clearance was required according to the regulations of the Ethics Committee of Ludwig-Maximilians-Universität München (LMU Munich).

Conflict of Interest Statement

PvP has received research funding from Germany's Federal Ministries of Food and Agriculture (BMEL), Education and Research (BMBF) and Environment and Consumer Protection (BMUV), as well as travel cost reimbursements and speaker and manuscript fees from the German and Austrian Nutrition Societies (DGE and ÖGE), among others. ER has received research funding from BMEL and BMBF. ML has received research funding from BMBF. OH is an employee of the German Diabetes Society (DDG) and the German Obesity Society (DAG) and has previously been an employee of foodwatch. The other authors have no conflicts of interest to declare.

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Author Contributions

P.v.P., O.H., A.L., D.R., J.B., K.E.F., S.P., M.L., and E.R.: methodology, writing – review and editing, and conceptualization; P.v.P. and A.L.: data curation and formal analysis; A.L.: validation; P.v.P.: writing – original draft; O.H. and P.v.P: funding acquisition.

Data Availability Statement

The Euromonitor International Passport data used in this research is proprietary data owned by Euromonitor International, a market research company. Access to the database has to be acquired from Euromonitor International and is generally subject to a fee. Further enquiries can be directed to the corresponding author.

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3. Projected health and economic impacts of sugar-sweetened beverage taxation in Germany: A cross-validation modelling study

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RESEARCH ARTICLE

Projected health and economic impacts of sugar-sweetened beverage taxation in Germany: A cross-validation modelling study

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Data Availability Statement: The source code for the microsimulation model (IMPACTNCD Germany) used in this study is available in an

Abstract

Background

Taxes on sugar-sweetened beverages (SSBs) have been implemented globally to reduce the burden of cardiometabolic diseases by disincentivizing consumption through increased prices (e.g., 1 peso/litre tax in Mexico) or incentivizing industry reformulation to reduce SSB sugar content (e.g., tiered structure of the United Kingdom [UK] Soft Drinks Industry Levy [SDIL]). In Germany, where no tax on SSBs is enacted, the health and economic impact of SSB taxation using the experience from internationally implemented tax designs has not been evaluated. The objective of this study was to estimate the health and economic impact of national SSBs taxation scenarios in Germany.

Methods and findings

In this modelling study, we evaluated a 20% ad valorem SSB tax with/without taxation of fruit juice (based on implemented SSB taxes and recommendations) and a tiered tax (based on the UK SDIL) in the German adult population aged 30 to 90 years from 2023 to 2043. We developed a microsimulation model ($IMPACT_{NCD}$ Germany) that captures the demographics, risk factor profile and epidemiology of type 2 diabetes, coronary heart disease (CHD) and stroke in the German population using the best available evidence and national data. For each scenario, we estimated changes in sugar consumption and associated weight change. Resulting cases of cardiometabolic disease prevented/postponed and related quality-adjusted life years (QALYs) and economic impacts from healthcare (medical costs) and

online repository at: https://github.com/kalleEF/IMPACT-NCD-Germany. The used demographic data (population size and composition including projections) can be freely accessed from the GENESIS database of the German Federal Statistical Office at https://www-genesis.destatis.de/genesis/online. Population size and composition are in Table 12411-0013; population projections are in Table 12421-0004. The used mortality data can be freely accessed from the German Federal Health Monitoring System at https://www.gbe-bund.de/gbe/ (Table: "Sterbefälle, Sterbeziffern (ab 1980) according to European Shortlist of Deaths"). The used anthropometric and nutritional exposure data is not freely available and is owned by the respective institutions (Helmholtz Zentrum München for the KORA cohorts; Max Rubner-Institut for the NVS II study). Access to the KORA data is possible upon application via https://helmholtz-muenchen.managed-otrs.com/external/ (contact: KORA.PASST@helmholtz-muenchen.de) and access to the scientific use file of the NVS II study is possible by application to SUF.NVS@mri.bund.de (further information at https://www.mri.bund.de/de/institute/ernaehrungsverhalten/forschungsprojekte/nvsii/scientific-use-file/). All other data is directly accessible in the Supporting Information S1 Appendix or via the used references.

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societal (medical, patient time, and productivity costs) perspectives were estimated using national cost and health utility data. Additionally, we assessed structural uncertainty regarding direct, body mass index (BMI)-independent cardiometabolic effects of SSBs and cross-validated results with an independently developed cohort model (PRIMEtime). We found that SSB taxation could reduce sugar intake in the German adult population by 1 g/day (95%-uncertainty interval [0.05, 1.65]) for a 20% ad valorem tax on SSBs leading to reduced consumption through increased prices (pass-through of 82%) and 2.34 g/day (95%-UI [2.32, 2.36]) for a tiered tax on SSBs leading to 30% reduction in SSB sugar content via reformulation. Through reductions in obesity, type 2 diabetes, and cardiovascular disease (CVD), 106,000 (95%-UI [57,200, 153,200]) QALYs could be gained with a 20% ad valorem tax and 192,300 (95%-UI [130,100, 254,200]) QALYs with a tiered tax. Respectively, €9.6 billion (95%-UI [4.7, 15.3]) and €16.0 billion (95%-UI [8.1, 25.5]) costs could be saved from a societal perspective over 20 years. Impacts of the 20% ad valorem tax were larger when additionally taxing fruit juice (252,400 QALYs gained, 95%-UI [176,700, 325,800]; €11.8 billion costs saved, 95%-UI [€6.7, €17.9]), but impacts of all scenarios were reduced when excluding direct health effects of SSBs. Cross-validation with PRIMEtime showed similar results. Limitations include remaining uncertainties in the economic and epidemiological evidence and a lack of product-level data.

Conclusions

In this study, we found that SSB taxation in Germany could help to reduce the national burden of noncommunicable diseases and save a substantial amount of societal costs. A tiered tax designed to incentivize reformulation of SSBs towards less sugar might have a larger population-level health and economic impact than an ad valorem tax that incentivizes consumer behaviour change only through increased prices.

Author summary

Why was this study done?

- Taxation of sugar-sweetened beverages (SSBs), recommended by the World Health Organization (WHO) and implemented in many jurisdictions globally, aims to reduce the noncommunicable disease burden by disincentivizing consumption through increased consumer prices or incentivizing industry reformulation to reduce SSB sugar content.
- No tax on SSBs is currently enacted in Germany and the national government is preparing a new national strategy on food seeking evidence-based recommendations to establish policy priorities until 2050.
- In Germany, the potential long-term health and economic impacts of SSB taxation have not been evaluated.

membership in the Doctoral Training Partnerships Representatives of the MRC; KMFEF, NW, MS, AP, LJC, MOF, PS, CK and ML report no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; JL reports membership in the scientific board and lead of working groups of the German Nutrition Society (DGE) and membership in the Scientific Advisory Board of the Federal Ministry of Food and Agriculture (BMEL); all authors report no other relationships or activities that could appear to have influenced the submitted work.

Abbreviations: BMI, body mass index; CHD, coronary heart disease; CVD, cardiovascular disease; GAMLSS, generalised additive models for location, shape and scale; NCD, noncommunicable disease; PUA, probabilistic uncertainty analysis; QALY, quality-adjusted life year; SDIL, Soft Drinks Industry Levy; SSB, sugar-sweetened beverage; T2DM, type 2 diabetes mellitus; UI, uncertainty interval; UK, United Kingdom; US, United States; WHO, World Health Organization.

What did the researchers do and find?

- We developed and validated a microsimulation model based on national data and international evidence to model the impact of SSB taxation on dietary exposure of added sugar from beverages, body mass index (BMI), cardiometabolic diseases, and related economic costs.
- We evaluated 3 SSB taxation scenarios in Germany with the simulation model: (1) 20% ad valorem tax on SSBs; (2) extended 20% ad valorem tax on SSBs and fruit juice; (3) tiered tax leading to reformulation of SSBs towards 30% lower sugar content.
- Taxation of SSBs in Germany could prevent or postpone 132,100 to 244,100 cases of type 2 diabetes, gain 106,000 to 192,300 quality-adjusted life years (QALYs) and save €10.8 to €16.0 billion in societal cost from 2023 to 2043 with the highest impacts estimated for tiered taxation.
- The absolute long-term health impacts are largely dependent on the relevance of direct, BMI-independent cardiometabolic effects of SSBs.

What do these findings mean?

- All modelled SSB taxation scenarios are likely to improve population health and reduce societal costs in Germany by preventing cardiometabolic disease.
- Considering all sources of uncertainty, we find that modelled SSB taxation scenarios that lead to reformulation towards less sugar might have a larger population-level health and economic impact than those that incentivize consumer behaviour change only through increased prices.
- From a public health perspective, taxation of SSBs should be considered as a policy option for German decision-makers to reduce consumption of added sugar and improve population health.

1. Introduction

In Central Europe, around 27% of premature deaths in 2017 were associated with dietary risk factors [1]. This is assumed to be a direct consequence of food environments fuelling unhealthy diets characterised by a high intake of energy-dense (often ultra-processed) foods high in fat, salt, and sugar [2]. Sugar-sweetened beverages (SSBs), usually defined as beverages with added caloric sweeteners (mostly high-fructose corn syrup and sucrose), are the main source of added sugars in global diets [3]. Excessive consumption of added sugars has been shown to increase morbidity and mortality, indirectly through excess calorie intake leading to weight gain and directly by increasing the risk for coronary heart disease (CHD), type 2 diabetes mellitus (T2DM), and dental caries [3].

To address the health and socioeconomic burden of unhealthy diets, the taxation of unhealthy foods is an important fiscal policy tool with the aim of disincentivizing consumption by increasing prices [4–6]. In recent years, government regulation of SSBs has been gaining traction and over 45 jurisdictions have implemented fiscal policies of which approximately 70% were enacted since 2015 [7]. Additionally, the World Health Organization (WHO) recommends SSB taxation as a best-buy policy to strengthen noncommunicable disease (NCD) prevention [6].

A recent meta-analysis synthesising ex post evaluations of implemented SSB taxation policies indicated that they indeed increase prices, decrease sales and, if designed with a tiered structure, are particularly effective in promoting reductions in added sugars by the food industry (i.e., via reformulation) [4]. A tiered structure here means that tax levels are differentiated based on beverage sugar content using predefined thresholds (e.g., 0.18 British pound sterling [£] per litre for drinks containing 5 to 8 grams [g] sugar per 100 millilitre [ml] and £0.24 per litre for drinks containing more than 8 g sugar per 100 ml in case of the Soft Drinks Industry Levy [SDIL] in the United Kingdom [UK]). However, although early observational studies indicate that SSB taxes could be effective in preventing obesity, generating robust empirical evidence on their impact on long-term health and economic outcomes is difficult [8,9].

In Germany, over 50% of the adult population are overweight and the prevalence of obesity has been increasing to almost 20% over the last years, following a clear socioeconomic gradient [10]. Assessment of the potentially related dietary risk factors is difficult because no regular surveillance of population dietary patterns exists. However, individual studies have shown that most of the population does not follow diet recommendations and that SSB consumption, particularly among younger age groups, is high [11,12].

To improve unhealthy diets, reduce the national burden of NCDs, and increase sustainability of the national food system, the German government is currently gathering recommendations for a national strategy on food [13]. This strategy will cover policy priorities until 2050 in domains such as procurement standards for meals (e.g., as developed by the German Nutrition Society), diet literacy, and sustainable food production [14]. Moreover, while the reduction of sugar in SSBs is a policy objective of the German government, a recent study found that voluntary industry commitments to reduce sugar in soft drinks were not successful [15]. A tax on SSB might be a suitable policy option which is also discussed by German decision-makers and supported by non-governmental organisations such as the German Alliance on NCDs [15].

Some studies have previously attempted to model the health impact of SSB taxation scenarios in Germany. However, these mainly used cohort modelling methods with lower granularity which are not able to account for complex epidemiological dependencies and population dynamics over time and did further not quantify healthcare cost savings or productivity losses [16–18]. The value of these previous studies in providing concrete policy recommendations might thus be limited. Yet, to promote best-practice, cost-effective policies, decision-makers need contemporary and context-specific evidence. This is highlighted by the political processes surrounding the enactment of SSB fiscal policies in Mexico and the UK for which timely scientific evidence played an important role [19].

In this study, we evaluate the impact of context-relevant SSB taxation scenarios in Germany on stroke, CHD, and T2DM morbidity, mortality and healthcare, patient time, and productivity costs with a new individual-level population health microsimulation model ($\text{IMPACT}_{\text{NCD}}$ Germany). Additionally, we explore structural uncertainty in the predicted policy impact by assessing the relevance of direct, body mass index (BMI)-independent cardiometabolic effects of SSBs and cross-validate our results with a second independently developed Markov cohort simulation model (PRIMEtime) [20–22].

2. Methods

Modelling overview

We evaluated 3 SSB tax policy scenarios that were chosen based on international scientific consensus recommendation and globally implemented SSB taxes accounting for context-relevant factors:

1. 20% ad valorem tax on SSBs based on scientific recommendations and implemented ad valorem or volumetric taxes in, e.g., Mexico, Chile, and United States (US) legislatures [4,6,7,23];
2. 20% ad valorem tax on SSBs and fruit juice, extending the tax to account for high consumption levels and the caloric content of juices [12];
3. 30% reformulation of SSBs towards lower sugar content based on tiered taxes such as the UK SDIL [4,7].

Further details on all scenarios and related assumptions are described below and in Methods A in S1 Appendix under "Policy module."

To simulate the health and economic impact of these SSB taxation scenarios, we developed and validated an NCD microsimulation model for Germany based on the UK $IMPACT_{NCD}$ framework ($IMPACT_{NCD}$ Germany; hereafter $IMPACT_{NCD}$). We modelled the German population age 30 to 90 years over 20 years (2023 to 2043) and performed an economic evaluation from healthcare and societal perspectives [24–27]. For this, we created a synthetic population stratified by age and sex that captures the real demographics, exposures, dietary intakes, and disease epidemiology of the actual German population using available national data sources (see below and in Methods A in S1 Appendix under "Epidemiological engine").

The main pathways of our model are founded on widely accepted epidemiological evidence and summarised in Fig 1. Briefly, in our main analysis we assumed that SSB taxation would, depending on the scenario, induce changes in SSB and fruit juice consumption or SSB sugar content guided by economic theory and observations from other countries in which taxes were implemented. We then modelled the effect of changed sugar consumption from SSBs and fruit juice on BMI and consequently BMI and SSB intake as exposures for T2DM, CHD, and stroke. Direct (BMI-independent) effects of SSBs on T2DM and CHD are assumed to be due to the added sugar they contain [21,28]. We also considered T2DM as a risk factor for CHD, stroke, and non-cardiovascular mortality. To analyse structural uncertainty, we (1) re-estimated all scenarios using only BMI-mediated effects, thus excluding the potentially more uncertain estimates of the direct cardiometabolic effects of SSBs from nutritional

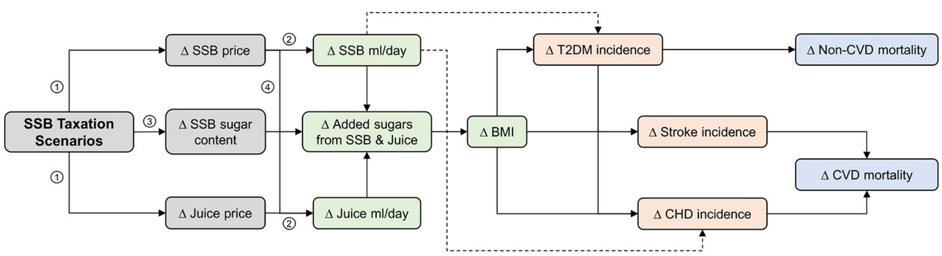

Fig 1. Policy, exposure, and disease pathways of the SSB tax modelling with $IMPACT_{NCD}$ Germany. Complete modelled pathways. Dashed arrows indicate direct effects of SSBs that are excluded in structural uncertainty analyses. Grey boxes indicate modelled policy pathways and corresponding numbered arrows denote underlying modelled mechanisms: (1) Economic theory suggests that SSB producers will pass some proportion of a tax on SSBs along to consumers via increased prices (tax pass-through). (2) After accounting for the tax pass-through rate, economic theory suggests that increased prices of SSBs lead to a change in SSB consumption based on their own-price elasticity of demand. (3) Tiered taxation with different tax rates according to SSB sugar content, incentivizes reformulation towards lower sugar content by producers to avoid the tax burden. (4) After accounting for the tax pass-through rate, economic theory suggests that increased prices of SSBs lead to substitution with similar goods such as fruit juice based on their cross-price elasticity of demand. Green boxes indicate exposures. Orange boxes and blue boxes indicate disease and mortality outcomes, respectively. Δ, "change in"; BMI, body-mass index; Juice, fruit juice; CHD, coronary heart disease; CVD, cardiovascular disease; ml, millilitre; SSB, sugar-sweetened beverages; T2DM, type 2 diabetes mellitus.

https://doi.org/10.1371/journal.pmed.1004311.g001 epidemiological studies [21]; and (2) cross-validated these results with the PRIMEtime cohort model (see below and Methods B and Methods C in S1 Appendix) [29].

Our model choice was guided by a previous review that we conducted during the Policy Evaluation Network project [30]. The technical details of both models have been described previously [20,26,27]. For an overview of all used parameters and data sources see Tables A and G in S1 Appendix. We provide the source code for $IMPACT_{NCD}$ in a public repository at https://github.com/kalleEF/IMPACT-NCD-Germany.

Sugar-sweetened beverage taxation scenarios

All SSB taxation scenarios including the additional taxation of fruit juice in Germany were modelled compared to a baseline without tax. SSBs were defined as (un-)caffeinated soft drinks or fruit drinks with added sugars (i.e., caloric sweeteners). Fruit juice was defined as 100% fruit juice and nectars or other types of juices that might contain added sugars. Unfortunately, we were not able to distinguish types of juices in detail. However, we consider the resulting bias as negligible because over 80% of consumed fruit juice in Germany does not contain added sugars [31].

The modelled SSB tax policy scenarios were based on globally implemented taxes and international scientific consensus recommendations [6,23]. Three scenarios were selected according to their relevance for the German context and considering limitations of the available beverage consumption data. The modelled scenarios were:

1. 20% ad valorem tax on SSBs (i.e., the tax is calculated as a proportion of the price) based on implemented ad valorem or volumetric taxes as for example in Mexico, Chile, and US legislatures [7]. Due to lack of access to product-level ingredient and price data, we could only approximate volumetric taxes through this scenario. However, most implemented taxes were designed to increase prices by 10% to 20% based on scientific recommendations [6,23]. Evidence has shown that such taxes indeed have increased prices and reduced SSB consumption (hereafter: "ad valorem tax") [4,6,7,23];
2. 20% ad valorem tax on SSBs and fruit juice that extends SSB taxation to account for the caloric content of fruit juices and the high baseline consumption in Germany (hereafter: "extended ad valorem tax");
3. tiered tax design with increasing tax rates according to specific sugar thresholds that incentivizes producers to reformulate SSBs towards 30% lower sugar content. This was based on observed reformulation effects under the UK SDIL, which could serve as a blueprint policy for other European countries such as Germany (hereafter: "tiered tax") [15,32,33].

Further details on the scenarios and their implementation in the model are described below and in Methods A in S1 Appendix under "Policy module."

Synthetic German population

To simulate the population-level impact of the policy scenarios, we constructed a synthetic German population. For this we combined (1) data on the exposures BMI and intake of SSBs and fruit juice from 3 waves of the Kooperative Gesundheitsforschung in der Region Augsburg (KORA) study (S4, F4, and FF4; 1999, 2007, and 2014), a population-based cohort in southern Germany, and the nationally representative dietary survey Nationale Verzehrsstudie (NVS) II (2006) [34–36]; (2) national data on the epidemiology of stroke, CHD, and T2DM [37]; and (3) information on death counts, population count estimates, and projections by age and sex from official sources and a de novo mortality forecast using a functional demographic model

(Methods A in S1 Appendix under "Mortality calibration") [38–41]. Detailed step-by-step descriptions of all data sources, applied statistical methods, and validation results for the synthetic population are described in Methods A in S1 Appendix under "Epidemiological engine."

Estimating exposure distributions

To estimate exposure distributions conditional on age and sex, we used generalised additive models for location, shape and scale (GAMLSS), which can handle complex relationships between the response variable and its predictors and numerous types of distributions [42]. For the distribution of BMI, we used data from the 3 KORA waves to incorporate time trends. In KORA FF4 usual dietary intakes were calculated using a blended approach consisting of up to three 24-h food lists and a food frequency questionnaire [35]. In NVS II dietary intakes were calculated based on two 24-h dietary recalls [34]. For the estimation of the SSB and fruit juice intake distributions in ml/day, we primarily relied on KORA FF4 and supplemented this with the NVS II due to the underrepresentation of younger age groups in KORA FF4. Our method accounts for non- and high-consumers in the beverage intake distributions via mixture models. We calculated sugar intake from SSBs and fruit juice using information on beverage-specific sugar consumption in g/ml that was available in KORA FF4. We adjusted beverage and sugar intake for misreporting with the residual method (i.e., regressed on energy intake) [43]. Further details are in Methods A in S1 Appendix under "Exposure module."

Estimating disease epidemiology

Information on the epidemiology of T2DM was gathered from the most recent data of the German national diabetes surveillance [37]. Due to data limitations for stroke and CHD incidence, we applied SCORE2 risk equations to the KORA data to estimate the yearly incidence of cardiovascular disease by age and sex [44, 45]. Incidence trends were based on the empirical trends between follow-ups S4, F4, and FF4. The proportions of stroke and CHD events in these estimates were based on results from the European Prospective Investigation into Cancer and Nutrition (EPIC) [46]. Finally, all epidemiological data was aligned and smoothed with DISMOD II before application in $\text{IMPACT}_{\text{NCD}}$ to improve consistency between incidence, prevalence, and mortality data [47]. Further details are in Methods A in S1 Appendix under "Disease module."

Effect of SSB taxation scenarios on sugar intake

According to economic theory, taxation can have both demand and supply side effects [48]. In the case of SSBs, taxation leads to increased consumer prices as producers pass some proportion of the tax along (i.e., tax pass-through) [48]. Price changes influence consumption of goods due to own- and cross-price elasticities of demand (i.e., %-change in consumption following price increase of the same or another product category by 1%) [49]. However, SSB taxes (e.g., the UK SDIL) can be designed with tax levels that depend on beverage sugar content and thus incentivize product reformulation, giving producers a way to avoid the tax. These mechanisms have important implications on implementing the analysed policy scenarios in our model. For further details, see Methods A in S1 Appendix under "Policy module."

In the "ad valorem tax" and "extended ad valorem tax" scenarios, the effect of price increases on SSB and fruit juice consumption was modelled with national price elasticities of demand. We first calculated the change in consumption of SSB and fruit juice and consequently the change in respective sugar intake. In the former we considered substitution from SSBs to fruit juice. In both scenarios, we assumed that the policy immediately affected beverage consumption. Because national elasticities were not available, we estimated de novo uncompensated price elasticities for beverage categories with an Almost Ideal Demand System using data from the German household consumption survey (Einkommens- und Verbrauchsstichprobe 2013 and 2018) (Methods A in S1 Appendix under "Policy module"). We estimated the own-price elasticity of SSBs and fruit juice to be −0.956 (95%-confidence interval [−1.174, −0.738], $p < 0.001$) and −1.106 (95%-CI [−1.397, −0.814], $p < 0.001$), respectively. The cross-price elasticity for SSBs and fruit juice was estimated to be 0.052 (95%-CI [−0.138, 0.242], $p = 0.593$) (Table J in S1 Appendix). Based on a recent meta-analysis, we assumed that the tax pass-through was 82% (95%-CI [66,98]; $p < 0.001$) [4].

To implement the effects of reformulation in the "tiered tax" scenario, we had to make several assumptions. Based on a recent evaluation of the UK SDIL, we assumed that individual intake of sugar from SSBs would be reduced by 30% without changing consumption [15]. We additionally assumed that this reduction would be gradually come into effect over 3 years. The reformulation effect can only be approximated since we did not have access to product-level data in the KORA or NVS studies and were thus unable to directly specify the underlying sugar thresholds. This means we assumed that a tiered tax, replicating the design of the UK SDIL and taking German SSB price levels and sugar content into account, would gradually lead to similar reformulation effects as in the UK.

Effects of exposures on cardiometabolic risk

For all modelled exposure and disease pathways in Fig 1, we used high-quality evidence from meta-analyses of prospective cohort studies or randomised controlled trials and cohort pooling projects to translate changes in sugar and SSB intake into changes in BMI and the risk for stroke, CHD, and T2DM. For simplicity, we considered the metabolic effects of sugar from SSBs and fruit juice on BMI to be the same [50].

We modelled the ceteris paribus effect of reduced consumption of sugar from beverages (i.e., no compensation behaviour beyond considered beverages) on the long-term reduction in BMI with effect estimates from a meta-analysis of prospective cohorts [51]. The predicted reductions in weight are conservative and generally lower than using traditional energy balance equations [52,53] (for comparisons, see Table G in S1 Appendix).

Like previous diet policy modelling studies, we considered (1) BMI-mediated effects on stroke, CHD, and T2DM risk [27,54,55]; (2) BMI-independent (direct) effects of SSBs on CHD and T2DM risk due to their sugar content [21,50,56]; and (3) T2DM as a risk factor for stroke, CHD, and non-cardiovascular mortality [57]. We included direct effects of SSBs to reflect potential underlying mechanisms related to insulin resistance and inflammation but excluded them in structural uncertainty analyses (see below) [21,50,58,59]. However, we did not model potential direct effects of fruit juice due to higher uncertainty in these estimates [21]. An overview of all used risk parameters can be found in Table G in S1 Appendix.

IMPACT$_{NCD}$ microsimulation

IMPACT$_{NCD}$ is a dynamic, discrete-time, stochastic, open-cohort microsimulation model that simulates the life course of individuals and their counterfactuals under alternative policy scenarios. It enables the detailed simulation of diet policies and their impact on relevant exposures, subsequent disease epidemiology, and mortality in a competing risk framework accounting for different lag-times between exposures and outcomes. The effect of individual exposure changes on disease risk is achieved with individualised attributable fractions (Methods A in S1 Appendix under "Disease module"). Our model was calibrated to observed (2013 to 2019) and future (2020 to 2043) non-cardiovascular (CVD) mortality rates projected with a functional demographic model [38]. Epidemiological and economic outputs of the model on a population level are highly flexible and aggregated from individual life courses. We mainly report (incident) cases and (prevalent) case-years prevented/postponed (i.e., either completely prevented or delayed by 1 or more years). A detailed technical description of the modelling process is given in Methods A in S1 Appendix.

Health-related medical, patient time, and productivity costs

We estimated medical, patient time, and productivity costs related to morbidity and mortality over the simulation period based on the life course of synthetic individuals. Economic impacts were calculated from healthcare and societal perspectives following contemporary economic evaluation guidelines using a human capital approach [60,61]. We assessed formal health sector costs by applying medical costs for the treatment of stroke, CHD, and T2DM from the newest available national evidence to each incident or prevalent case year [62,63]. In the societal perspective, we additionally assessed informal health sector (i.e., patient time costs for T2DM self-management and health services use) and productivity costs (i.e., sick leave days and early retirement associated with stroke and T2DM and premature death) [64]. These were valued according to published national estimates, except premature death costs that were calculated using average annual gross wages including fringe benefits [65–68]. Medical and patient time costs were applied until death, while productivity losses accumulated until the German retirement age of 65 years. We inflated health sector costs, informal health sector costs, and productivity losses to 2022 prices using the German medical sector price index and the German labour cost index (see Methods A in S1 Appendix under "Health economics module") [69,70]. All costs were discounted at 3% per year [71].

Quality-adjusted life years

Cumulative quality-adjusted life years (QALYs) over the simulation period were estimated taking the health-related quality of life of synthetic individuals, including morbidity and mortality, over their life course into account. For this, we re-estimated recently published national health utility decrements accounting for age, sex, BMI, stroke, CHD, and T2DM to improve consistency with our analysis (see Methods A in S1 Appendix under "Health economics module") [72]. QALYs were discounted at 3% per year [71].

Uncertainty and sensitivity analyses

$\text{IMPACT}_{\text{NCD}}$ incorporates stochastic (first-order) and parameter (second-order) uncertainty, as well as individual heterogeneity with extensive probabilistic (Monte Carlo) uncertainty analyses (PUA) using 500 iterations [73,74]. We also assessed structural uncertainty in the predicted policy impact with regards to BMI-independent effects of SSBs by re-estimating all scenarios using only BMI-mediated effects (Fig 1) [74].

We conducted several sensitivity analyses to contextualise our results by providing further comparison scenarios and varying important policy-related assumptions. We modelled: (1) impacts of observed voluntary reformulation of SSBs by industry (i.e., 2% per 6 years) [15]; (2) the tiered tax scenario with reformulation by 10%; (3) tax rates of 10% and 30% for the "ad valorem tax" scenario; (4) the "ad valorem tax" scenario without substitution effects to fruit juice (i.e., setting the cross-price elasticity to 0); (5) the impact of price changes on SSB consumption with a meta-analytic estimate [75]; (6) a maximum impact scenario that combines reformulation and consumption reduction; and (7) varied discount rates for costs and QALYs (0%, 5%, and 10%). Further details on uncertainty and sensitivity analyses are available in Methods A and B in S1 Appendix.

Model validation

We performed extensive analyses to validate $IMPACT_{NCD}$ according to current guidelines [29]: (1) To ensure internal and face validity, the computational implementation, model outputs, and structure were discussed during meetings among the author group. We also compared inputs and model outputs of disease-specific prevalence and incidence and assessed the ability of the model to track past observed and projected mortality (Fig S–AD in S1 Appendix). (2) To assess external validity, we compared simulated disease-specific epidemiological data from the baseline scenario to comparable external information not used to inform model inputs (Fig AE–AM in S1 Appendix). (3) To cross-validate the predicted policy impact, we modelled all policy scenarios with an adapted version of PRIMEtime, which is a discrete-time proportional multistate life table Markov cohort model. Due to PRIMEtime's preexisting structure, cross-validation was performed for the analysis including only BMI-mediated effects. As cross-validation targets, we used disease-specific cases prevented/postponed and QALYs. We minimised potential differences between models, by generating exposure and epidemiological inputs for PRIMEtime based on the synthetic German population; using the same data sources where possible; and aligning preexisting disease risk parameters. Uncertainty in PRIMEtime was separately assessed with 1,000 PUA iterations and only includes parameter (second-order) uncertainty. Technical descriptions of PRIMEtime have been published previously [20,76]. See Methods B and C in S1 Appendix for an overview of PRIMEtime and an extensive description of the cross-validation.

Patient and public involvement

No patients or members of the public were involved in the design and conduct of this study or the interpretation of its results. The results of this study will be shared as policy briefs with public representatives. We acknowledge that this analysis would not have been possible without data from participants of the respective cohort and survey studies.

3. Results

We estimated that a national tax on SSBs and/or juice would decrease consumption of sugar from these beverages in Germany by 1 g/day (95%-uncertainty interval [UI] [0.05 to 1.65]) in the "ad valorem tax" scenario; 5.91 g/day (95%-UI [5.37, 6.04]) in the "extended ad valorem tax" scenario and 2.34 g/day (95%-UI [2.32, 2.36]) in the "tiered tax" scenario (Table 1). An overview of all exposure changes by scenario is given in Table S in S1 Appendix. Over 20 years, all modelled scenarios would have a positive impact on population health in Germany, reducing obesity, saving healthcare costs, and leading to productivity gains (Table 2 and Fig 2). This finding was robust, irrespective of the simulation model used and whether direct effects of sugar in SSBs were considered, albeit estimated impacts were a lot lower when excluding them (Fig 2). We mainly focused on the results including all exposure pathways in the following sections. See Tables T–Z in S1 Appendix for stratified and additional analyses.

Health impact of SSB taxation scenarios

A 20% ad valorem tax (scenario: "ad valorem tax") on SSBs could prevent/postpone around 1,900 cases of stroke (95%-UI [0, 4,500]), 39,200 cases of CHD (95%-UI [21,100, 58,100]), 132,100 cases of T2DM (95%-UI [61,700, 202,900]), and 31,600 (95%-UI [−5,400, 72,600]) cases of obesity, compared to the counterfactual without the policy, and 1,109,300 (95%-UI [481,700, 1,838,200]) case-years lived with T2DM and 733,800 (95%-UI [99,600, 1,431,500]) case-years lived with obesity could be mitigated (Table 2).

Table 1. Changes in sugar consumption from SSBs and juice under different policy scenarios in Germany by sex and age groups.

Sex and age group	Change in sugar consumption from SSBs and juice compared to baseline without tax (95%-uncertainty intervals)		
	Ad valorem tax*	Extended ad valorem tax#	Tiered tax‡
	Absolute change from 2023 to 2043 in g/day		
Male			
30–49 years	−2.87 (−3.82, −1.36)	−10.19 (−10.44, −9.28)	−6.11 (−6.22, −6.02)
50–69 years	−1.32 (−2.04, −0.24)	−6.81 (−6.99, −6.17)	−2.99 (−3.04, −2.94)
70–90 years	−0.57 (−1.03, 0.12)	−4.09 (−4.21, −3.69)	−1.39 (−1.42, −1.35)
Female			
30–49 years	−0.90 (−1.69, 0.26)	−6.93 (−7.12, −6.28)	−2.24 (−2.27, −2.20)
50–69 years	−0.44 (−1.06, 0.43)	−5.17 (−5.32, −4.67)	−1.25 (−1.27, −1.23)
70–90 years	−0.22 (−0.64, 0.36)	−3.36 (−3.47, −3.03)	−0.70 (−0.71, −0.68)
Total	*−1.00 (−1.65, −0.05)*	*−5.91 (−6.04, −5.37)*	*−2.34 (−2.36, −2.32)*
	Relative change from 2023 to 2043 in %		
Male			
30–49 years	−4.73 (−6.35, −2.24)	−16.97 (−17.44, −15.48)	−10.12 (−10.34, −9.94)
50–69 years	−3.55 (−5.45, −0.67)	−18.03 (−18.60, −16.33)	−8.02 (−8.17, −7.86)
70–90 years	−2.53 (−4.57, 0.44)	−17.91 (−18.50, −16.14)	−6.17 (−6.30, −6.02)
Female			
30–49 years	−2.23 (−4.28, 0.68)	−17.44 (−18.01, −15.84)	−5.60 (−5.71, −5.50)
50–69 years	−1.58 (−3.78, 1.54)	−18.36 (−18.98, −16.57)	−4.46 (−4.54, -4.38)
70–90 years	−1.17 (−3.46, 2.03)	−18.41 (−18.99, −16.51)	−3.71 (−3.79, -3.64)
Total	*−2.94 (−4.80, −0.18)*	*−17.15 (−17.54, −15.60)*	*−6.85 (−6.92, -6.79)*

Absolute and relative changes in sugar consumption (in grams per day) from SSBs and juice under different policy scenarios in Germany by sex and age groups.

*"Ad valorem tax" refers to a 20% ad valorem tax on SSBs with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios").

#"Extended ad valorem tax" refers to a 20% ad valorem tax on SSBs and fruit juice with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios").

‡"Tiered tax" refers to a tiered tax on SSBs similar to the UK SDIL that leads to a reduction in SSB sugar content by 30% through reformulation (for details, see section "Sugar-sweetened beverage taxation scenarios").

g, grams; SSB, sugar-sweetened beverages; UK SDIL, United Kingdom Soft Drinks Industry Levy.

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Expanding the tax to fruit juice (scenario: "extended ad valorem tax") would lead to increased overall health gains (cases prevented/postponed: 4,500 for stroke, 95%-UI [1,900, 8,500]; 45,800 for CHD, 95%-UI [27,500, 66,200]; 190,800 for T2DM, 95%-UI [112,000, 269,700]) (Table 2), and the largest impact on obesity, particularly among women due to their relatively high fruit juice consumption (Methods A in S1 Appendix under "Exposure module"). Obesity cases prevented/postponed would increase to 109,700 (95%-UI [70,400, 162,200]) for men and 50,500 (95%-UI [22,100, 80,900]) for women (Table X in S1 Appendix).

In the "tiered tax" scenario, health impacts for CHD and T2DM were substantially higher than in the "(extended) ad valorem tax" scenarios. Here, the cases prevented/postponed increased to 3,400 for stroke (95%-UI [800, 7,100]), 69,800 for CHD (95%-UI [38,800, 101,900]), 244,100 for T2DM (95%-UI [118,200, 365,300]), and 72,300 (95%-UI [36,400, 105,500]) for obesity (Table 2).

Table 2. Health and economic impact of different SSB taxation scenarios in Germany 2023–2043 from healthcare and societal perspectives.

Health outcomes	**Change in outcomes compared to baseline without tax (95%-uncertainty intervals)**		
	Ad valorem tax*	**Extended ad valorem tax#**	**Tiered tax‡**
Cases prevented/postponed†			
T2DM	132,100 (61,700, 202,900)	190,800 (112,000, 269,700)	244,100 (118,200, 365,300)
CHD	39,200 (21,100, 58,100)	45,800 (27,500, 66,200)	69,800 (38,800, 101,900)
Stroke	1,900 (0, 4,500)	4,500 (1,900, 8,500)	3,400 (800, 7,100)
Obesity	31,600 (−5,400, 72,600)	159,400 (97,100, 232,400)	72,300 (36,400, 105,500)
Case-years prevented/postponed†			
T2DM	1,109,300 (481,700, 1,838,200)	1,569,600 (876,500, 2,313,800)	1,940,900 (879,200, 3,106,500)
CHD	239,700 (112,300, 375,600)	274,700 (146,600, 415,100)	408,200 (206,600, 620,900)
Stroke	4,300 (−6,600, 22,200)	18,600 (2,300, 50,200)	8,900 (−6,600, 32,300)
Obesity	733,800 (99,600, 1,431,500)	3,919,200 (2,340,700, 5,490,500)	1,683,100 (1,035,800, 2,341,000)
All-cause deaths prevented/postponed	17,000 (8,600, 26,100)	21,600 (12,600, 31,800)	29,300 (15,900, 44,900)
QALYs gained	106,000 (57,200, 153,200)	252,400 (176,700, 325,800)	192,300 (130,100, 254,200)
Life years gained	95,400 (47,300, 161,000)	114,200 (61,300, 187,300)	156,700 (77,900, 255,400)
Difference in life expectancy	0.02 (−0.01, 0.05)	0.02 (−0.01, 0.06)	0.03 (0.00, 0.08)
Difference in life expectancy at age 60 years	0.01 (−0.01, 0.02)	0.01 (−0.01, 0.03)	0.01 (−0.01, 0.04)
Health-related cost outcomes (€-millions)			
Healthcare costs			
T2DM	−1,613 (−2,750, −684)	−2,310 (−3,492, −1,311)	−2,785 (−4,601, −1,249)
CHD	−660 (−1,003, −345)	−792 (−1,170, −461)	−1,136 (−1,631, −619)
Stroke	−89 (−225, 0)	−204 (−425, −84)	−153 (−364, −35)
Other	118 (59, 202)	144 (77, 236)	190 (97, 326)
Productivity costs			
T2DM early retirement	−24 (−60, 5)	−35 (−73, −3)	−41 (−101, 4)
T2DM sick leave	−1,170 (−2,809, −384)	−1,536 (-3,427, -541)	−2,013 (−4,707, −610)
Stroke early retirement	−1 (−33, 5)	−5 (−70, 0)	−3 (−62, 3)
Stroke sick leave	0 (−1, 0)	0 (−3, 0)	0 (−2, 0)
Premature death	−3,556 (−7,135, −1,260)	−3,904 (−7,388, −1,518)	−5,913 (−10,999, −2,265)
Time costs			
T2DM self-management	−1,146 (−2,020, −475)	−1,461 (−2,420, −730)	−1,941 (−3,368, −863)
T2DM time for health service use	−1,446 (−3,508, −502)	−1,892 (−4,424, −718)	−2,470 (−5,667, −847)
Other time for health service use	374 (153, 651)	485 (239, 781)	633 (269, 1,068)
Cost-effectiveness			
Total change in costs from healthcare perspective (€-millions)	−2,262 (−3,596, −1,189)	−3,141 (−4,568, −1,942)	−3,850 (−6,075, −2,070)
Total change in costs from societal perspective (€-millions)	−9,584 (−15,304, −4,714)	−11,827 (−17,887, −6,702)	−16,013 (−25,500, −8,090)
ICER$ (healthcare perspective)	Dominant	Dominant	Dominant
ICER$ (societal perspective)	Dominant	Dominant	Dominant

*"Ad valorem tax" refers to a 20% ad valorem tax on SSBs with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios").

#"Extended ad-valorem tax" refers to a 20% ad valorem tax on SSBs and fruit juice with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios").

‡"Tiered tax" refers to a tiered tax on SSBs similar to the UK SDIL that leads to a reduction in SSB sugar content by 30% through reformulation (for details, see section "Sugar-sweetened beverage taxation scenarios").

†Cases and case-years prevented/postponed are defined as incident and prevalent cases completely prevented or delayed for 1 or more years, respectively.

$Expressed as € per QALY. Only defined for positive incremental costs and else "dominant" because no trade-off exists if health is improved while costs are saved.

CHD, coronary heart disease; ICER, incremental cost-effectiveness ratio; QALY, quality-adjusted life year; SSB, sugar-sweetened beverages; T2DM, type 2 diabetes mellitus; UK SDIL, United Kingdom Soft Drinks Industry Levy.

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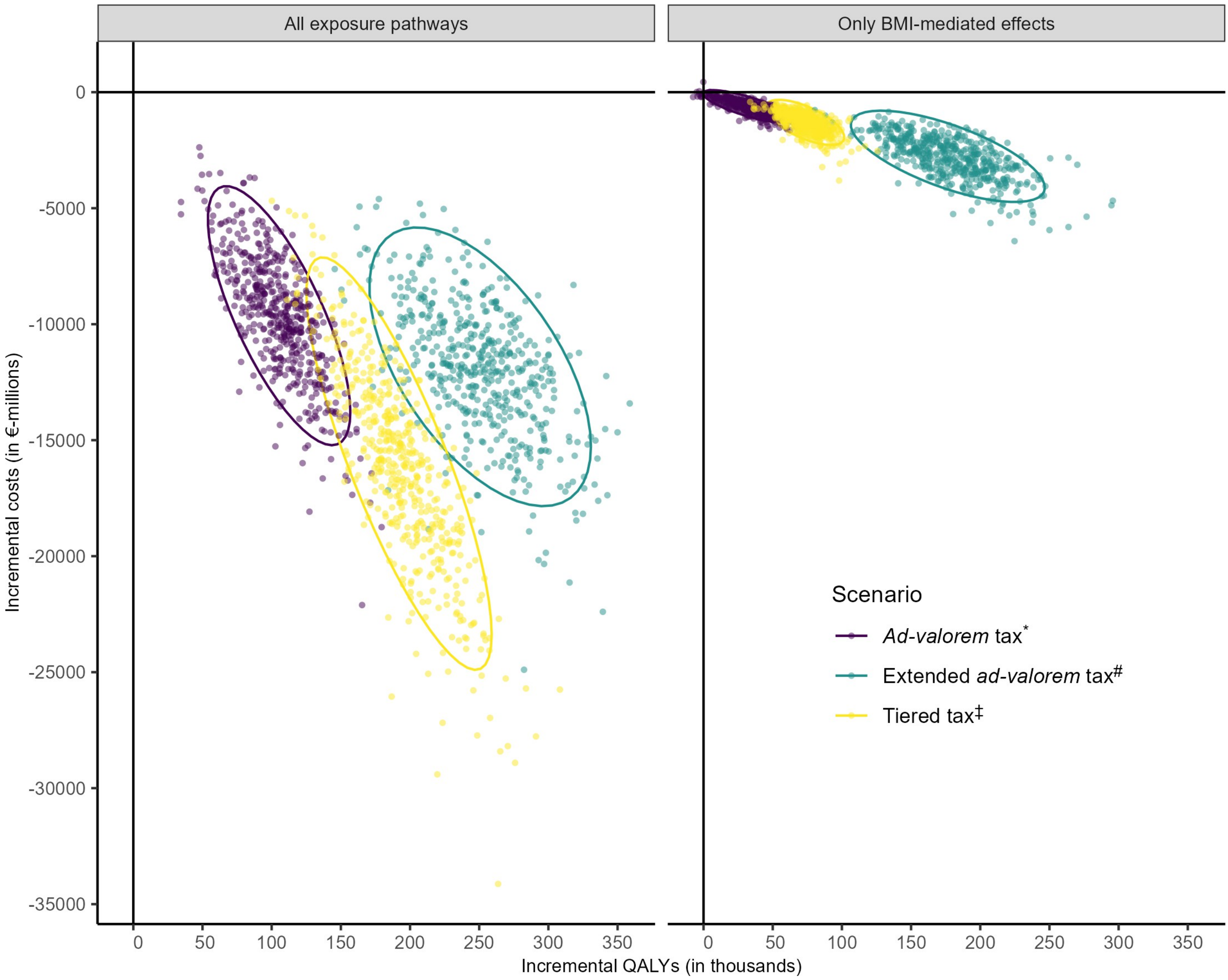

Fig 2. Cost-effectiveness plane for different SSB taxation scenarios in Germany 2023–2043 from a societal perspective. Cost-effectiveness plane showing incremental (i.e., compared to baseline without tax) QALYs on the x-axis and incremental costs from a societal perspective on the y-axis by scenario and included exposure pathways. Ellipses indicate 95%-uncertainty intervals of incremental QALYs and costs per scenario assuming a multivariate t-distribution. *"Ad valorem tax" refers to a 20% ad valorem tax on SSBs with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios"). #"Extended ad valorem tax" refers to a 20% ad valorem tax on SSBs and fruit juice with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios"). ‡"Tiered tax" refers to a tiered tax on SSBs similar to the UK SDIL that leads to a reduction in SSB sugar content by 30% through reformulation (for details, see section "Sugar-sweetened beverage taxation scenarios"). BMI, body mass index; QALY, quality-adjusted life year; SSB, sugar-sweetened beverages; UK SDIL, United Kingdom Soft Drinks Industry Levy.

https://doi.org/10.1371/journal.pmed.1004311.g002

For all scenarios, the policy impact was highest among men due to their higher baseline SSB consumption, particularly in younger ages. Most cases of stroke, CHD, and T2DM would be prevented in the age groups below 70 years (Table W in S1 Appendix).

Economic impact of SSB taxation scenarios

Healthcare costs saved, productivity loss averted and QALYs gained over the 20-year simulation period were substantial in all scenarios and mirror the reported health impacts in their

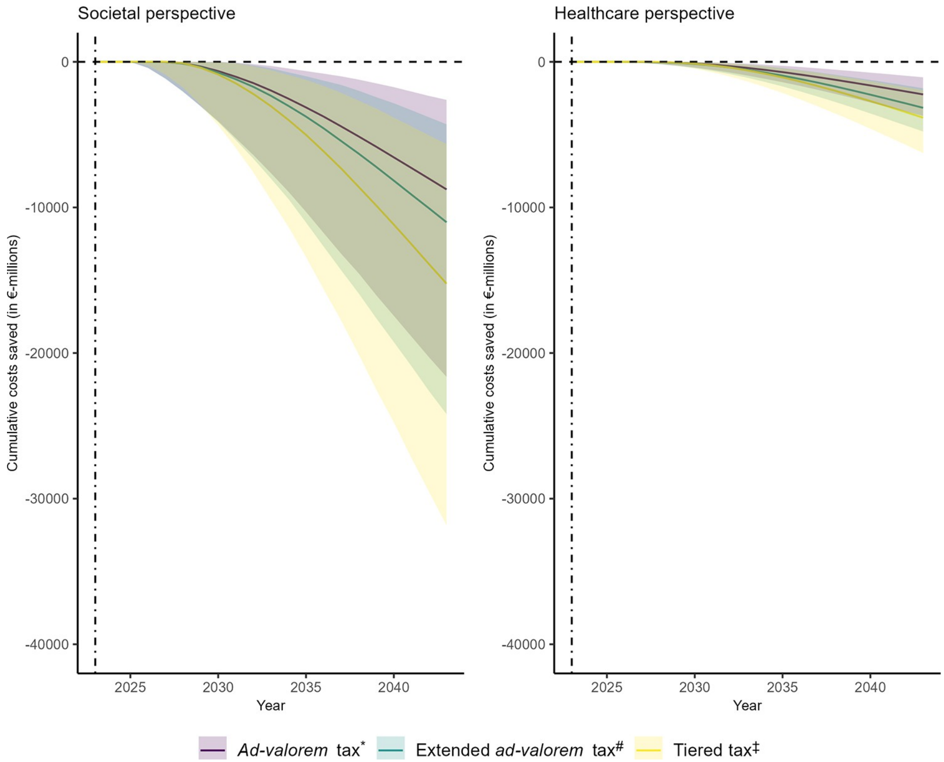

Fig 3. Cumulative costs saved through SSB taxation from 2023 to 2043 by scenario and health economic perspective. Line plots of median cumulative costs saved in €-millions from 2023 to 2043 as a consequence of SSB taxation scenarios stratified health economic perspective. Shaded areas indicate 95%-uncertainty intervals. *"Ad valorem tax" refers to a 20% ad valorem tax on SSBs with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios"). #"Extended ad valorem tax" refers to a 20% ad valorem tax on SSBs and fruit juice with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios"). ‡"Tiered tax" refers to a tiered tax on SSBs similar to the UK SDIL that leads to a reduction in SSB sugar content by 30% through reformulation (for details, see section "Sugar-sweetened beverage taxation scenarios"). SSB, sugar-sweetened beverages; UK SDIL, United Kingdom Soft Drinks Industry Levy.

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relative magnitude between policy scenarios and distribution according to sex and age (Table 2, Tables W and X in S1 Appendix). All 3 policy scenarios were cost-saving and dominant from healthcare and societal perspectives compared to their counterfactual without SSB taxation (Fig 2). Cumulative cost savings over time per scenario and perspective are shown in Fig 3. The total QALYs gained were 106,000 (95%-UI [57,200, 107,100]) for the "ad valorem tax," 252,400 (95%-UI [176,700, 325,800]) for the "extended ad valorem tax," and 192,300 (95%-UI [130,100, 254,200]) for the "tiered tax." We estimated that from a healthcare perspective €2,262 million (95%-UI [€1,189, €3,596]) costs could be saved with the "ad valorem tax"; €3,141 million (95%-UI [1,942, 4,568]) with the "extended ad valorem tax"; and €3,850 million (95%-UI [€2,070, €6,075]) with the "tiered tax." The largest share of disease-specific costs saved in all scenarios was due to T2DM (Table 2). From a societal perspective, economic gains were many times bigger (€9,584 million, 95%-UI [€4,714, €15,304] savings for the "ad valorem tax"; €11,827 million, 95%-UI [€6,702, €17,887] for the "extended ad valorem tax"; €16,013 million, 95%-UI [€8,090, €25,500] for the "tiered tax"). Productivity gains were largely determined by the prevention of premature deaths and T2DM-related sick leave and time costs (Table 2).

Validation results

IMPACT$_{NCD}$ performed very well in internal and external validation analyses (Fig S–AM in S1 Appendix). In the cross-validation with PRIMEtime, we found that both models estimated similar health impacts, supporting the overall robustness of our findings. Uncertainty in IMPACT$_{NCD}$ was generally higher than in PRIMEtime but for all scenarios and outcomes, uncertainty intervals overlapped (Fig 4, Fig AN and AO in S1 Appendix).

Structural uncertainty and sensitivity analyses

When excluding direct, BMI-independent effects of SSBs, the health and economic impact across all scenarios, particularly on T2DM and CHD, was considerably smaller (Fig 2, Table Y in S1 Appendix). Here, the largest health gains would be achieved in the "extended ad valorem tax" scenario (177,600 QALYs gained, 95%-UI [121,500, 242,300]; €2,704 million costs saved from societal perspective, 95%-UI [€1,345, €5,002]). However, considering only SSBs, the "tiered tax" would on average produce larger benefits (73,500 QALYs gained, 95%-UI [51,600,

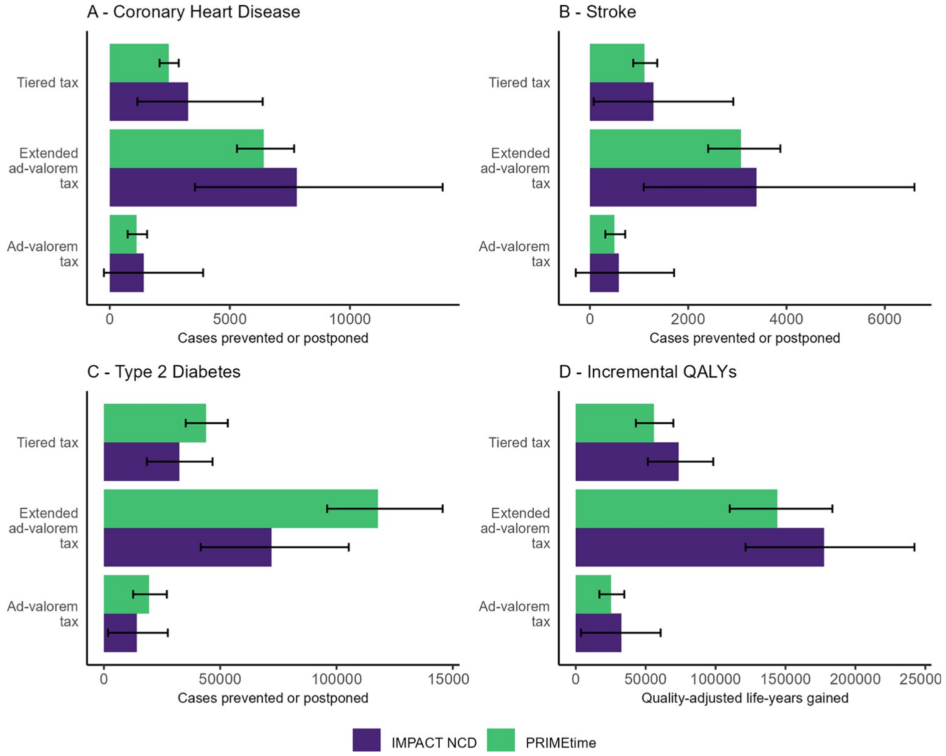

Fig 4. Cross-validation results of IMPACT$_{NCD}$ Germany and PRIMEtime with key health outcomes. Horizontal bar chart comparing cross-validation outcomes for (A) CHD cases prevented/postponed, (B) stroke cases prevented/postponed, (C) type 2 diabetes cases prevented/postponed, and (D) QALYs gained between the IMPACT$_{NCD}$ microsimulation (purple) and the PRIMEtime cohort model (green). Only BMI-mediated exposure pathways are modelled. Error bars indicate 95%-uncertainty intervals. "Ad valorem tax" refers to a 20% ad valorem tax on SSBs with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios"). "Extended ad valorem tax" refers to a 20% ad valorem tax on SSBs and fruit juice with a pass-through to consumers of 82% (for details, see section "Sugar-sweetened beverage taxation scenarios"). "Tiered tax" refers to a tiered tax on SSBs similar to the UK SDIL that leads to a reduction in SSB sugar content by 30% through reformulation (for details, see section "Sugar-sweetened beverage taxation scenarios"). BMI, body mass index; NCD, noncommunicable disease; QALY, quality-adjusted life year; SSB, sugar-sweetened beverages; UK SDIL, United Kingdom Soft Drinks Industry Levy.

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98,400]; €1,292 million costs saved from societal perspective, 95%-UI [€620, €2,292]) than estimated in the "ad valorem tax" scenario (32,600 QALYs gained, 95%-UI [3,700, 60,700]; €589 million costs saved from societal perspective, 95%-UI [€128, €1,352]). A detailed comparison for all health and economic outcomes is available in Table Y in S1 Appendix.

Health and economic impacts changed sometimes significantly when varying the tax rate for the "ad valorem tax" scenario between 10% (change in QALYs: −43%) and 30% (+48%), excluding substitution effects from SSBs to fruit juice (+6%), or implementing the effect of taxation using a meta-analytic estimate (−25%); decreasing reformulation for the "tiered tax" to 10% (−66%); or varying the discount rate for costs and QALYs (−66% to +30% depending on the discount rate and scenario). We estimated that observed voluntary industry commitments to reduce sugar content in SSBs would only gain 16,400 QALYs and that a combined reformulation and consumption reduction of SSBs would lead with 322,200 QALYs gained to the highest impact (Tables T–V in S1 Appendix).

4. Discussion

We use established epidemiological evidence and national data to develop the first population health microsimulation model for Germany ($IMPACT_{NCD}$), which we apply to estimate the health and economic impact of 3 SSB taxation scenarios. Our study suggests that the implementation of a German national ad valorem or tiered tax on SSBs following international scientific recommendations and examples such as Mexico and the UK and considering the additional taxation of fruit juice, could lead to substantial health gains (approximately 106,000 to approximately 250,000 QALYs gained) and save a substantial amount of costs from both healthcare (approximately €2,300 to approximately €3,800 million) and societal perspectives (approximately €9,600 to approximately €16,000 million) over the next 20 years. We find that a reduction of SSB sugar content, as observed following the introduction of the UK SDIL, is likely to lead to higher health gains and averted costs than the consumption reduction that could be expected from a 20% ad valorem tax without any reformulation. We show that the additional taxation of fruit juice would lead to increased health gains in the "ad valorem tax" scenario and could be justified due to high consumption levels in Germany. In sensitivity analyses, we find that health impacts that can be expected from observed voluntary industry commitments to reduce sugar in SSBs are negligible compared to the modelled SSB taxation scenarios. We also estimate that the health and economic impact of SSB taxation is considerably higher, if potential direct (BMI-independent) effects of sugar in SSBs are confirmed but that a substantial policy impact can still be expected if only established BMI-mediated effects on cardiometabolic outcomes are considered. Results from validation analyses encourage trust in the model which cross-validated well with the independently developed PRIMEtime cohort model.

Our study is consistent with international modelling studies that have shown that SSB taxation may lead to substantial long-term health and economic impacts, primarily through a reduction in BMI due to lower sugar consumption and the prevention of T2DM [28,77–79]. However, we explicitly show that the quantification of the SSB taxation impact depends to a large degree on the relevance of direct, BMI-independent health effects of SSBs from nutritional epidemiological studies which few modelling studies have considered [28,30]. By transparently reporting the resulting uncertainty, we provide a corridor for the predicted policy impact and highlight the need for robust causal epidemiological estimates. To the best of our knowledge, our study is the first diet policy evaluation to compare individual-level and cohort modelling approaches and with 2 separate, independently developed simulation models. Similar efforts have so far only been made for diabetes- and cancer-specific, clinically oriented models but are very important to improve the quality and trustworthiness of modelling studies [80,81].

We add to the few previous simulation-based studies which have analysed the potential impact of SSB taxation in Germany by providing a much more comprehensive and detailed analysis of different policy scenarios based on real-world examples [16–18]. While we come to the same overall conclusion that taxation of SSBs is very likely to have positive impacts on population health, we can provide concrete policy guidance that a tax design focusing on SSB sugar content is likely most effective. However, this depends to some degree on the relevance of BMI-independent health effects of SSBs. We also quantify the positive cardiometabolic health effects of SSB taxation in Germany and the substantial societal economic impact from productivity losses and patient time costs for T2DM self-management which is more than twice as high as the averted medical costs.

Our findings are supported by evidence on the increase of SSB prices under volumetric or ad valorem taxation, corresponding reductions in SSB purchases and observed reformulation under tiered taxation [4,32,48,82–84]. Robust evidence from randomised trials and cohort studies shows that increased sugar and SSB consumption leads to weight gain [3,85,86]. Recently, observational evidence on the effect of implemented SSB taxes on anthropometric outcomes is emerging [8].

A particular strength of our approach is the use of an established modelling framework, which enables the detailed, flexible simulation of the health of the German population under different scenarios. To our knowledge, we are the first to model the full health and economic impact of SSB taxation on cardiometabolic health in Germany based on international scientific recommendations and implemented policies. Further, our model validates very well, including on externally observed data, and we adhere to transparency guidelines by making all code available in a public repository. We comprehensively consider implications of all sources of uncertainty from parameter uncertainty to the included risk relationships and the chosen simulation method, which has not been done before in population health modelling. This makes our findings particularly robust. Finally, we provide concrete policy recommendations for the new German national strategy on food and beyond.

However, several limitations need to be considered. First, Germany lacks a regular health examination survey that includes granular, individual-level dietary intake data, and the last official national nutrition survey is from 2007 [12]. We therefore had to rely primarily on the KORA S4 cohort study with its 2 follow-ups F4 and FF4 (1999 to 2014) for anthropometric and nutrition data that was designed to be population representative of the Augsburg region in southern Germany [36]. Thus, full representation of the German population with regards to the modelled exposures might be biased and should be addressed in future iterations of the model if appropriate data sources are available. Second, we were not able to include time trends in beverage consumption which was only collected in FF4. A comparison with annual, industry-reported, aggregated beverage consumption data indicates that (1) SSB and juice intake in Germany has remained stable; (2) SSB consumption is likely underreported; and (3) juice consumption may be overreported (Methods A in S1 Appendix under "Exposure module"). Third, we do not account for health effects beyond CVD and T2DM. Fourth, we do not consider cumulative effects of sugar intake over the life course. Fifth, we do not incorporate heterogeneity in price elasticities by age, sex, or other characteristics. Additionally, our elasticities were estimated with data prior to the recent rise in inflation. However, according to economic theory, price elasticities should generally be higher during inflation as real income diminishes. Sixth, we did not include health effects in children or adolescents. Importantly, the above limitations are unlikely to meaningfully impact our results, but indeed most likely lead to underestimation of the policy impact. Seventh, we cannot perform a detailed simulation of

SSB taxes depending on the sugar content of certain products, such as the SDIL, because we do not have access to product-level data. This also does not allow us to perform a standardised comparison of different tax designs or to distinguish tax-related price and reformulation effects in the tiered tax scenario. The interpretation of the relative effectiveness of the simulated tax designs should be made with these limitations in mind. Similarly, in the "ad valorem tax" scenario, we approximate the effects of volumetric taxes which were most often designed to increase prices by 10% to 20% [48]. Eighth, we have neither included costs of implementing an SSB tax, nor industry reformulation costs. Because no good guidance on SSB tax implementation cost exists, previous studies have for example assumed that these would be around 2% of the tax payments [87] or general administrative and auditing costs [88]. However, while implementation costs might be higher for tiered taxes due to their more complex design, considering the estimated population-level economic impacts these are negligible. Finally, as with all population health modelling studies, our results are subject to the validity of the underlying economic and epidemiological evidence including the employed estimates of long-term weight change. We account for the arising epistemic uncertainty by relying on high-quality risk estimates from decades of research and by incorporating as many sources of uncertainty in our simulations as possible.

Our findings have implications for German health and fiscal policy makers and the new national food strategy. We provide evidence that SSB taxation is a cost-effective tool to address the burden of NCDs in Germany. While we acknowledge that voluntary industry commitments to reduce SSB sugar content are in place, a previous analysis has shown that they fail to achieve targeted reductions [15]. We demonstrate that SSB taxation would lead to approximately 10 times larger healthcare cost savings compared to these voluntary commitments. We particularly show that focusing on reductions of SSB sugar content, for example, through a tax design incentivizing reformulation like the UK SDIL, might have larger health and economic impacts than ad valorem taxation of SSBs with moderate tax rates. This finding is consistent with a study from the US [28]. Achieving both a reduction in sugar content of SSBs and their consumption would be most effective. Considering that government efforts to reduce sugar content in SSBs through voluntary commitments were unsuccessful, the introduction of a tiered tax levied on producers, taking the UK SDIL as a blueprint, which gives producers the option to avoid the tax, seems most feasible in the German context.

Recent data from the UK government shows that the tax revenue from the SDIL accumulates to more than £300 million per year even after the observed product reformulation [89]. While earmarking of tax revenues to specific purposes is not possible in Germany, these resources could be acknowledged in fiscal negotiations about social and healthcare budgets for NCD preventive measures, ideally striving to alleviate existing health disparities in disadvantaged groups [2]. While we do not calculate the projected tax revenue in our study, it is important to note that different SSB tax designs have implications for this potentially relevant outcome. Since tiered taxes are designed to incentivize reformulation (i.e., to avoid the tax), their revenue might be lower than for ad valorem or volumetric taxes [90].

Based on our findings and from a public health perspective, the additional taxation of fruit juice in Germany could be justified as well, considering high consumption levels [91,92]. In fact, we predict the largest reduction in sugar consumption under the "extended ad valorem tax" (including fruit juice). Yet, this would not translate to the largest health gains if BMI-independent, direct effects of SSBs are considered. However, considering international experiences, the taxation of fruit juice is unlikely [7].

To curb the health, economic, and environmental burden of unhealthy diets over the life course, a comprehensive, population-based multicomponent policy approach transforming the food system is needed [2,93]. This is key to enable citizens to live a healthy life and protect particularly children and adolescents from negative health consequences in adulthood. Further, the German population is progressively ageing and population-based policies which prevent NCDs, such as T2DM, which increase the likelihood for early retirement, can contribute to sustain macroeconomic productivity.

Our study supports the rationale that fiscal policies (i.e., health taxes) which address specific nutritional components or food groups should be considered key preventive policies similarly to those for tobacco control [5,94]. As such they can address negative health externalities resulting from diet-related NCDs [95]. Additionally, negative effects on employment and industry have thus far not been observed [96,97]. Structural health policies such as SSB taxation are also more likely to improve health equity overall compared to alternative, often high-agency, policies like information campaigns [98]. However, one caveat of fiscal policies is that they might be regressive [95].

To further improve the accuracy of population health modelling studies and their relevance for policy makers generally and specifically in Germany many avenues for future research exist. First, the quantification of causal effects of the cross-sectoral, multidimensional, and heterogenous behavioural response to health and social policies is of particular importance [9]. This will both, improve our understanding of policy mechanisms and lead to better projections from policy simulations. Second, while simulation models are most useful for comparing potential future policy scenarios, they can also be useful for monitoring the impact of observed exposure changes within a holistic policy evaluation framework. Here, quasi-experimental methods can be used in conjunction with novel data sources to estimate causal short- and mid-term effects of policies, while simulation models use these estimates to project long-term implications which are infeasible to observe due to identification problems [9,99]. Third, future studies should also aim to find ways of comparing outcomes from real-world evaluations of NCD policies with simulation modelling studies to improve long-term predictions [9]. Fourth, more evidence on established and potential dietary risk factors, such as artificially sweetened beverages, is needed, which ideally provides causal estimates and takes food matrix effects into account [2]. A better understanding of dietary risks, obesity incidence, and health will also lead to better NCD policy modelling studies. Finally, in Germany a better surveillance of dietary and metabolic risk factors across population strata is key to enable the identification of vulnerable population subgroups and assess the equity impact of policies. Addressing these gaps will enable better, timely policy recommendations and ideally improve population health outcomes.

In conclusion, the introduction of a 20% ad valorem or tiered SSB tax in Germany, based on scientific recommendations and taxes implemented in countries like Mexico or the UK, could help to reduce the national burden of cardiometabolic NCDs and save a substantial amount of healthcare and productivity costs. A tiered tax designed to incentivize reformulation of SSBs towards less sugar might have a larger population-level health and economic impact than an ad valorem tax that incentivizes consumer behaviour change only through increased prices.

Supporting information

S1 Appendix. Supplemental methods and results. Detailed methodological description of the applied simulation models, including all preparatory analyses, model parameters and data sources. Additionally, extensive results tables and figures for all sensitivity analyses.
(DOCX)

S1 File. Consolidated Health Economic Evaluation Reporting Standards (CHEERS) 2022 statement.
(DOCX)

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Part III.

Appendix

A. Additional publications

A.1. Simulation modeling for the economic evaluation of population-based dietary policies: a systematic scoping review

Bibliographic information:

Title:	Simulation modeling for the economic evaluation of population-based dietary policies: a systematic scoping review
Authors:	**Karl M. F. Emmert-Fees**, Florian M. Karl, Peter von Philipsborn, Eva A Rehfuess, and Michael Laxy on behalf of the Policy Evaluation Network (PEN) consortium
Journal:	*Advances in Nutrition*
Year:	2021
Volume:	12(5)
Pages:	1957-1995
DOI:	10.1093/advances/nmab028
Impact factor:	9.3 (Clarivate Journal Citation Reports™ 2022)
Journal Rank:	3/88 (1st Quartile) in *Nutrition and Dietetics* (Clarivate Journal Citation Reports™ 2022)

Summary of methods and results:‡

The specific aims of the review were first to map existing applications of simulation models that evaluated the health and economic impact of population-based diet policies, secondly to give an overview of the applied types of simulation models, and finally to discuss strengths and limitations highlighting avenues for future research in the application of simulation modeling to evaluate diet policies.

We opted to conduct a systematic scoping review because our research question was not suitable for the application of a classical systematic review. In accordance with concurrent guidelines, all procedures and analytical steps for the scoping review were predefined and a protocol was prospectively published in an OSF repository† on February 4, 2020 (osf.io/63kpu). Studies were eligible for inclusion in the mapping if they were original contributions that performed an economic evaluation of an explicitly specified diet policy using a simulation model. To identify eligible studies, we searched three electronic literature databases with restrictions to studies published in English between 2005 and February 4, 2020. We additionally conducted forward and backward citation searching of all eligible studies. Although not required, we conducted a quality appraisal of included studies using a specifically adapted version of the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) checklist. Key results were mapped visually using innovative visualisations and used to construct a logic model of the conceptual pathways of diet policy evaluations. We also summarized

‡We explicitly do not provide references in this short summary and refer to the respective publication.

key information on the simulation modeling techniques that were applied in the reviewed studies in the corresponding supplementary material.

After screening 6845 studies, we included 56 modeling studies which contained 136 applications of simulation models that estimated the health and economic impact of diet policies. The majority of studies was conducted HIC countries, particularly the US, UK, and Australia, and published after 2010 with a particular increase observed after 2015. The quality of the included studies was mixed, with only approximately half meeting 90% or more of the predefined checklist items. In terms of dietary policies, the included studies covered a broad spectrum of 78 unique policies including educational policies, point-of-purchase information policies, reformulation policies, and fiscal policies. Very few assessed comprehensive multi-component diet policies. Policies targeted various nutritional aspects, predominantly salt/sodium and SSBs, but also fruit and vegetables, trans-fatty acids (TFAs), and processed meat, among others. However, there was a considerably undercomplexity of how diet is represented and only few studies analysed policies addressing food processing or overall diet quality. The most frequently modelled diseases were CVD, diabetes, and cancer the impact of diet on which was modelled via BMI, blood pressure, and cholesterol as intermediate clinical risk factors. We identified four primary simulation model types that were applied: comparative risk assessment (CRA) models, Markov cohort models, MSLT models, and microsimulations. The latter were the only model type that simulated individuals instead of homogeneous cohorts over time. Particularly the application of these individual-level models has increased in recent years to evaluate more complex diet policies. A detailed description of model types based on example studies is available in the supplementary material of the published study (Appendix A.1). However, it has to be considered that we only included modeling studies that conducted an economic evaluation and could thus not draw conclusions about purely epidemiological modeling studies. With regards to health economic outcomes, the majority of studies only included costs in the healthcare sector but did not consider wider economic impacts of diet policies such as productivity losses or caregiver time costs. While we did not directly compare cost-effectiveness outcomes between policies and settings, 76% of evaluated policies were considered cost-saving. Importantly, only few studies assessed equity implications of diet policies.

We point to several methodological aspects that could be addressed by future studies to advance the field: 1) There is considerable heterogeneity in model structures but the impact of the underlying structural assumptions, which are made by researchers, has not been thoroughly assessed and different types of models have not been compared; 2) the validity of the underlying effect estimates at all steps of the hypothesized causal pathway from policy to health and economic outcomes should be improved; 3) behavioral adaption mechanisms to policies could be included in models to improve validity of long-term projections; and 4) transparency in reporting and validation of simulation models in the evaluation diet policies is largely lacking and quality standards may improve trust of stakeholders.

† The international prospective register for systematic reviews PROSPERO does not accept scoping reviews.

REVIEW

Simulation Modeling for the Economic Evaluation of Population-Based Dietary Policies: A Systematic Scoping Review

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ABSTRACT

Simulation modeling can be useful to estimate the long-term health and economic impacts of population-based dietary policies. We conducted a systematic scoping review following the PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews) guideline to map and critically appraise economic evaluations of population-based dietary policies using simulation models. We searched Medline, Embase, and EconLit for studies published in English after 2005. Modeling studies were mapped based on model type, dietary policy, and nutritional target, and modeled risk factor–outcome pathways were analyzed. We included 56 studies comprising 136 model applications evaluating dietary policies in 21 countries. The policies most often assessed were reformulation (34/136), taxation (27/136), and labeling (20/136); the most common targets were salt/sodium (60/136), sugar-sweetened beverages (31/136), and fruit and vegetables (15/136). Model types included Markov-type (35/56), microsimulation (11/56), and comparative risk assessment (7/56) models. Overall, the key diet-related risk factors and health outcomes were modeled, but only 1 study included overall diet quality as a risk factor. Information about validation was only reported in 19 of 56 studies and few studies (14/56) analyzed the equity impacts of policies. Commonly included cost components were health sector (52/56) and public sector implementation costs (35/56), as opposed to private sector (18/56), lost productivity (11/56), and informal care costs (3/56). Most dietary policies (103/136) were evaluated as cost-saving independent of the applied costing perspective. An analysis of the main limitations reported by authors revealed that model validity, uncertainty of dietary effect estimates, and long-term intervention assumptions necessitate a careful interpretation of results. In conclusion, simulation modeling is widely applied in the economic evaluation of population-based dietary policies but rarely takes dietary complexity and the equity dimensions of policies into account. To increase relevance for policymakers and support diet-related disease prevention, economic effects beyond the health sector should be considered, and transparent conduct and reporting of model validation should be improved. *Adv Nutr* 2021;00:1–39.

Keywords: public health nutrition, dietary policy, policy evaluation, simulation modeling, economic evaluation, non-communicable disease prevention, systematic scoping review

Introduction

Noncommunicable diseases (NCDs) are the leading cause of morbidity and mortality, responsible for 73% of deaths and 62% of disability-adjusted life-years (DALYs) globally (1, 2). They also result in a staggering economic burden affecting health care systems and societies at large (3, 4). Unhealthy dietary behavior (especially high salt, sugar, and *trans* fatty acid (TFA) intake; low intake of fruit and vegetables; and high consumption of energy-dense foods) is one of the main modifiable risk factors for cardiometabolic NCDs, such as cardiovascular disease (CVD), type 2 diabetes, and obesity, as well as certain types of cancer (5).

To improve population health, many national and local governments implement population-based dietary policies such as nutrient or food (group)-specific taxes and subsidies, mandatory nutritional standards, or packaging requirements (e.g., labels or size caps), which can be more affordable, sustainable, effective, and cost-effective than downstream prevention or chronic disease care (6–11).

For the economic evaluation of these policies, simulation modeling methods such as comparative risk assessments (CRAs), Markov cohort, or microsimulation models can be used to (ex ante) estimate potentially complex long-term health and economic effects under different scenarios

 Adv Nutr 2021;00:1–39; doi: https://doi.org/10.1093/advances/nmab028.

and policy options (12). Building on the most recent evidence, these methods can integrate data on relevant dietary components, risk factors, and NCDs from different sources, represent population heterogeneity, and incorporate various uncertainties (12, 13). Because NCD outcomes manifest over decades and policy implementation costs arise immediately, projections from simulation models can provide an important basis for public policy decisions in the absence of direct observational or experimental evidence.

Although simulation models that use an epidemiological model structure to perform economic evaluations of public health interventions—so-called public health economic simulation models [as defined by Briggs et al. (12)]—have been extensively applied in the evaluation of dietary policies (14–16), no systematic assessment and critical appraisal of these studies has been performed (17).

The application of scoping review methodology gives us the opportunity to discuss the range of applied modeling methods, evaluated dietary policies, important contextual factors, and modeling assumptions and limitations in a more open format. The results of this work are relevant for policymakers and applied researchers seeking to conduct and judge dietary policy evaluations.

This systematic scoping review aims to 1) map applications of public health economic simulation models in population-based dietary policy, 2) examine model types that are applied, and 3) discuss the context and limitations of economic evaluations of dietary policies using such models, highlighting gaps and opportunities. We also provide detailed information on important model types and their exemplary implementation in the **Supplemental Material**.

Methods

In this systematic scoping review, we accounted for 3 levels of information: modeling studies, model applications, and model types. We created a systematic overview and mapping of modeling studies and model applications within them. A model application was defined as the public health economic simulation model-based evaluation of a dietary policy in a specific country within a modeling study. We extracted high-level information about each model application with regard to policies and aimed to identify patterns, limitations, and gaps in published research.

In the Supplemental Material, we have described the conceptual model structure, modeling methods, risk factor–outcome mechanisms, main assumptions, limitations, validation information, and transparency of exemplary implementations of important model types in more detail.

PRISMA-ScR and protocol

We followed published methods for the conduct of scoping reviews and reported this review according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist (18–21). Our protocol was prospectively registered on the Open Science Framework on 4 February 2020 (osf.io/63kpu and **Supplemental Methods 1**), to which we refer the reader for an extensive account of the methods used in this systematic scoping review.

Eligibility criteria

We included articles if they were 1) original studies, 2) conducting an economic evaluation of 3) explicitly specified population-based dietary policies, and 4) using 1 or more public health economic simulation models.

We used the term economic evaluation in accordance with Drummond et al. (22) denoting the comparative analysis of health outcomes and costs under different policy scenarios.

A population-based dietary policy was defined as a policy with the aim of improving the nutritional status of the general population (adults and children or adults only) on a national or sufficiently large subnational geographic and legislative level, as opposed to specific subgroups, high-risk individuals, or settings. Although dietary policies at a subnational level (e.g., city) might differ from national policies, we included studies evaluating these policies to account for the varying legislative authority of different levels of government in some countries (e.g., taxation at a city level).

Public health economic simulation models are defined in line with Briggs et al. (12) as simulation models that combine an epidemiological model structure with disease cost and health state utility information to perform economic evaluations of public health interventions or policies.

We excluded articles focusing on children, refugees, food system workers, or indigenous people and very specific settings (e.g., workplace cafeterias). This is justified because dietary policies specifically aimed at population subgroups such as children require different, although nonetheless important, policy (and potentially modeling) approaches, which were beyond the scope of this review (23).

In line with our protocol, we decided post hoc to further exclude studies evaluating food-fortification policies or applying macro-econometric modeling.

We treated validation studies of simulation models in the context of dietary policy and publications or reports

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Author disclosures: The authors report no conflicts of interest.

Supplemental Results 1, Supplemental Figure 1, Supplemental Tables 1-4 , and Supplemental Methods 1–4 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/advances/.

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Abbreviations used: CHD, coronary heart disease; CHEERS, Consolidated Health Economic Evaluation Reporting Standards; CRA, comparative risk assessment; CVD, cardiovascular disease; DALY, disability-adjusted life-year; HALY, health-adjusted life-year; ICER, incremental cost-effectiveness ratio; LY, life-year; LYG, life-years gained; NCD, noncommunicable disease; QALY, quality-adjusted life-year; SSB, sugar-sweetened beverage; TFA, *trans* fatty acid.

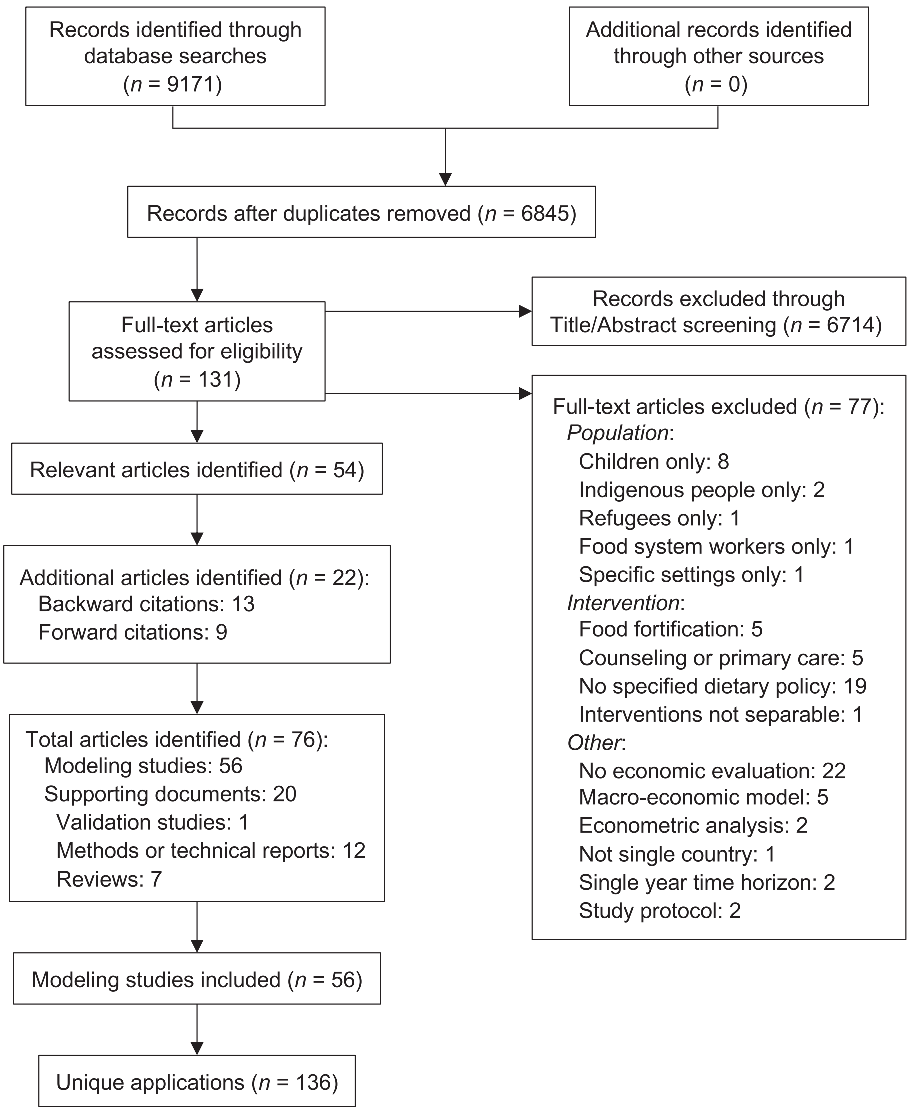

FIGURE 1 PRISMA flow diagram. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

concerned with simulation modeling methods in general as supporting documents that were not included in the mapping process. An overview of these can be found in **Supplemental Table 1**.

Information sources and search strategy

We searched the bibliographic databases Embase, MEDLINE, and EconLit for potentially eligible articles and applied forward and backward citation searching to all eligible articles (**Figure 1**).

The search strategy was pre-tested and comprised 4 broad categories of search terms: diet, policy, economic evaluation, and simulation modeling. Search results were limited to original studies and reviews published in English between 1 January 2005 and 4 February 2020 (**Supplemental Methods 2**).

Selection of sources of evidence, data charting, and data items

Two review authors (KMFE-F, FMK) independently screened the titles and abstracts of potentially eligible articles using Rayyan (24). Conflicts were resolved by consensus and, in the case of continued disagreement, by discussion with a third review author (ML).

One review author (KMFE-F) extracted data from modeling studies, model applications, and model types using a predefined data-extraction form, and all extracted items were checked by a second review author (FMK) (**Table 1**; **Supplemental Table 2** and **Supplemental Methods 3**). Important definitions and key terms are defined below.

For definitions related to cost and costing perspective, we adhered to recommendations from the Second Panel on Cost-Effectiveness in Health and Medicine (25). In health economics, the costing perspective defines the scope and cost

TABLE 1 Summary of included modeling studies and applications conducting an economic evaluation of dietary policies[1]

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Allen et al. 2015 (26), England	1	Ban on TFAs in processed foods	FE - I	Str	7900 QALYs gained; −£264 to −£64 mil net costs	+	Mortality: CHD; LYG; QALYs	HC; IC priv and pub; PC; ICC	English adults aged ≥25 y	IMPACTsec	CRA	S	5 y	Yes	Yes	Assumed decline in CHD mortality proportional to CHD incidence; only TFAs in processed foods; potential measurement bias in relevant TFA intake; effect of TFA based on meta-analysis from 2006; aggregate measure of deprivation
	2	Improved labeling of TFAs (processed foods)	FE - N	S-A	4000 QALYs gained; −£115 to −£22 mil net costs	+										
	3	Ban on TFAs in restaurants (processed foods)	FE - O	Str	2100 QALYs gained; −£47 to £0 mil net costs	+										
	4	Ban on TFAs in takeaways (processed foods)	FE - O	Str	3000 QALYs gained; -£75 to −£13 mil net costs	+										
Amies-Cull et al., 2019 (27), England	5	UK government sugar-reduction program	FE - I	S-A	51,729 QALYs gained; −£286 mil net health care cost	+	Incidence: CVD, stroke, diabetes, cancers, cirrhosis; QALYs	HC	English adults aged 18–80 y	PRIMEtime-CE (based on PRIME and ACE-prevention)	MSLT	(NHS)	10 y	(Y)	No	Potential response bias in underlying data (underreporting in nutrition surveys); relative risks based on observational data; validation with external datasets not possible; simplistic weight change estimation
An, 2015 (28), USA	6	Implementation of Healthy Incentives Pilot in SNAP (FV)	FE - U	S-A	0.082 ΔQALYs/person gained; $1323 Δcost/person; ICER: $16,172/QALY; NMB (WTP: $50k–$100k): $2767–$6857	−	QALYs	IC pub	US SNAP participant households	Generic	Markov	G	L	No	No	Assumed permanent price effect on consumption; dose-response might be nonlinear; health benefit of fruit and vegetables may not be fully captured by reduced mortality (e.g., HRQoL); some costs of the intervention not captured; HRQoL data and life table from 2003 and 2010
Basto-Abreu et al. 2019 (29), Mexico	7	SSB excise tax	FE - U	S-A	1 peso/liter: 55,300 QALYs gained; 5840 DALYs averted; −$91.62 mil net health care costs; $3.98 saved per dollar invested	+	Incidence: diabetes, stroke, IHD, HHD, cancers; QALYs; DALYs	HC; IC pub	Mexican population age 2–100 y	Generic (based on CHOICES/ACE-prevention)	MSLT	EHS	10 y	(Y)	No	Potential response bias in underlying data (dietary recall); effect on weight is assumed to be linear across different intake levels and age ranges; disease effects beyond BMI not modeled

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Basu et al., 2013 (16), USA	8	SSB purchase ban in SNAP	FE - I	Str	99,000 QALYs gained; −$285 mil net costs; ICER: cost-saving	+	Diabetes PY; mortality: MI, stroke; QALYs	HC; net T and S cost	US adults aged 25–64 y	Generic	Microsimulation	EHS	10 y	(Y)	Yes	Potential response bias in underlying data; assumed stable physical activity levels; direct impact of price changes, not on level of producer; no location-specific data (food deserts); potential unpredictable impact on future food prices; no information on heterogeneity within SNAP population; no children
	9	SSB tax	FE - U	S-A	26,000 QALYs gained; −$13.106 bil net costs; ICER: cost-saving	+										
	10	Fruit and vegetable subsidy	FE - U	S-A	7700 QALYs gained; $6.777 bil net costs: ICER: $876,500/QALY	−										
	11	Fruit and vegetable reward	FE - U	S-A	Not significantly different from zero	−										
Carter et al., 2019 (30), Australia	12	Junk food tax (snacks/sweets and SSBs)	FE - U	S-A	DALYs averted only in graph; -$911 mil net costs	+	Mortality: IHD, HHD, stroke, diabetes, cancers; DALYs; LYG	HC; PC	Australian adults aged ≥20 y	ACE- obesity and LifeLoss-MOD	MSLT and microsimulation	S	27 y	(Y)	No	Productivity impacts of reduced obesity-related morbidity not accounted for; excluded productivity gains from unpaid labor
Cecchini et al., 2010 (14), Brazil	13	Fat tax and healthy subsidy (FV and fat)	FE - U	S-A	20 years: 1642 DALYs per mil population; ICER: cost-saving	+	DALYs; LYs	HC; IC pub	General Brazilian population	OECD-WHO Chronic Disease Prevention Model	Microsimulation	GCEA	100 y	No	No	Not all potential confounding factors considered; potentially unknown (long-term) intervention effects; health behavior of children born during simulation based on mothers; social multiplier effects not accounted for; no difference between urban and rural settings
	14	Food labeling (overall nutrient composition)	FE - N	S-A	20 years: 1030 DALYs per mil population; ICER: $9962/DALY	−										
China	15	Fat tax and healthy subsidy (FV and fat)	FE - U	S-A	20 years: 1027 DALYs per mil population; ICER: cost-saving	+			General Chinese population							
	16	Food labeling (overall nutrient composition)	FE - N	S-A	20 years: 779 DALYs per mil population; ICER: $71/DALY	−										
England	17	Fat tax and healthy subsidy (FV and fat)	FE - U	S-A	20 years: 1,496 DALYs per mil population; ICER: cost-saving	+			General English population							

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
	18	Food labeling (overall nutrient composition)	FE - N	S-A	20 years: 1134 DALYs per mil population; ICER: $12,577/DALY	−										
India	19	Fat tax and healthy subsidy (FV and fat)	FE - U	S-A	20 years: 139 DALYs per mil population; ICER: cost-saving	+			General Indian population							
	20	Food labeling (overall nutrient composition)	FE - N	S-A	20 years: 495 DALYs per mil population; ICER: $952/DALY	−										
Mexico	21	Fat tax and healthy subsidy (FV and fat)	FE – U	S-A	20 years: 509 DALYs per mil population; ICER: cost-saving	+			General Mexican population							
	22	Food labeling (overall nutrient composition)	FE - N	S-A	20 years: 358 DALYs per mil population; ICER: $3974/DALY	−										
Russia	23	Fat tax and healthy subsidy (FV and fat)	FE - U	S-A	20 years: 1696 DALYs per mil population; ICER: cost-saving	+			General Russian population							
	24	Food labeling (overall nutrient composition)	FE - N	S-A	20 years: 1176 DALYs per mil population; ICER: $396/DALY	−										
South Africa	25	Fat tax and healthy subsidy (FV and fat)	FE - U	S-A	20 years: 528 DALYs per mil population; ICER: cost-saving	+			General South African population							
	26	Food labeling (overall nutrient composition)	FE - N	S-A	20 years: 389 DALYs per mil population; ICER: $7953/DALY	−										
Choi et al., 2017 (31), USA	27	Fruit and vegetable subsidy in SNAP	FE - U	S-A	0.24 ΔQALYs/person gained; −$823.74 Δcost/person; ICER: cost-saving	+	Incidence: T2D, MI, stroke, obesity; QALYs	HC; IC pub	General US population	Generic	Microsimulation	EHS	L	(Y)	Yes	Nutritional associations may be false-positive; more evidence on kilocalorie effect size of fruit and vegetable intake needed; potential response bias in underlying data; risk equations may overestimate risk

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Cleghorn et al., 2019 (32), New Zealand	28	SSB serving size cap	FE - I	S-A	82,100 QALYs gained; −$1.62 bil net cost	+	QALYs	HC	General New Zealand population	BODE[3]	MSLT	HS	L	Yes	No	No package size data availability and assumption that nobody switched to larger serving, potentially leads to overestimation; SSB consumption data from 2008; potential response bias in underlying data (only single dietary recall); impact on dental health not modeled; no children
Cobiac et al., 2010a (33), Australia	29	Voluntary sodium reformulation and labeling (Tick Programme)	FE - I and FE - N	S-A	5300 DALYs averted; −A$23.3 mil net costs; ICER: cost-saving	+	DALYs	HC; IC priv and pub	General Australian population	ACE- prevention	MSLT	LS	L	No	No	Preventive effects of blood pressure reduction are assumed to be realized within 1 y; assumed gradual decline of CVD incidence and case fatality in first 20 y of analysis
	30	Mandatory sodium reformulation	FE - I	Str	110,000 DALYs averted; −A$461 mil net costs; ICER: cost-saving	+										
Cobiac et al., 2010b (34), Australia	31	Community events and and promotion of fruit and vegetables	BCC - I	S-A	5200 DALYs averted; −A$7 mil net costs; ICER: cost-saving; P (<$50,000/DALY): 94%	+	DALYs	HC; IC pub	General Australian population aged ≥18 y	ACE- prevention	MSLT	EHS	L	No	No	Unknown sustainability of behavior changes; assumed exponential decay of effect at a rate of 50% per year; effect of repeated intervention unclear; health consequences of change in fat intake associated with the intervention not explicitly modeled; relationship between food groups and disease outcomes still poorly understood (micronutrient pathways not modeled); incorporating costs of health for unrelated diseases in added years of life will change results

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ^2	VD	Key authors' limitations
Cobiac et al., 2012 (35), Australia	32	Mandatory salt reformulation (breads, margarines, and cereals)	FE – I	Str	80,000 DALYs averted; −A$846 mil net costs; ICER: cost-saving	+	DALYs	HC; IC pub	General Australian population	Generic	Markov	EHS	L	No	No	Average population effect is assumed to be sustained with ongoing implementation
Cobiac et al., 2017 (36), Australia	33	Saturated fat tax	FE - U	S-A	97,000 DALYs averted; −A$1248 mil net costs; ICER: cost-saving; P(<$50,000/DALY): 100%	+	DALYs	HC; IC pub	General Australian population	ACE- prevention	MSLT	EHS	L	No	No	Price elasticity estimates from New Zealand; potential reformulation has no impact on consumer preferences; high uncertainty about the possible causal pathways between diet and disease
	34	Sodium tax	FE - U	S-A	130,000 DALYs averted; −A$1528 mil net costs; ICER: cost-saving; P(<$50,000/DALY): 100%	+										
	35	SSB tax	FE - U	S-A	12,000 DALYs averted; −A$258 mil net costs; ICER: cost-saving; P(<$50,000/DALY): 99%	+										
	36	Fruit and vegetable subsidy	FE - U	S-A	−13,000 DALYs averted; A$2162 mil net costs; ICER: dominated; P(<$50,000/DALY): 16%	−										
	37	Sugar tax	FE - U	S-A	270,000 DALYs averted; −A$2678 mil net costs; ICER: cost-saving; P(<$50,000/DALY): 100%	+										
Collins et al., 2014 (37), England	38	Health promotion campaign (salt) (Change4Life)	BCC - I	Agt	1970 LYG; −£392 mil net costs	+	LYG	HC; IC priv and pub	General English population	IMPACT CHD	CRA	(LS)	10 y	No	No	Assumed single-step change in policy; patient numbers after intervention assumed to remain constant; future health care costs are not included; potential changes in taste of products and preferences of consumers are not considered
	39	Salt labeling	FE - N	S-A	1970 LYG; −£397 mil net costs	+										
	40	Voluntary salt reformulation	FE - I	S-A	14,593 LYG; −£584 mil net costs	+										
	41	Mandatory salt reformulation	FE - I	Str	19,365 LYG; −£669 to −£186 mil net costs	+										

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Crino et al., 2017 (38), Australia	42	SSB reformulation	FE - I	S-A	144,621 HALYs gained; −$1.3 bil net costs; ICER: cost-saving	+	HALYs	HC; IC priv and pub	General Australian population aged 2–100 y	Generic	MSLT	LS	L	(Y)	No	Direct evidence supporting the impact of the intervention on consumer behavior is weak; SSB package size data not available; costs for changes in packaging and reformulation are not sourced; revenue loss for food industry and impact on consumers not considered
	43	SSB package size cap	FE – I	S-A	73,883 HALYs gained; −$540.9 mil net costs; ICER: cost-saving	+										
Dalziel and Segal, 2007 (39), Australia	44	Information campaign ("2 fruit 5 veg every day")	BCC - I	Agt	0.0048 ΔQALYs/person gained; $0.20 Δcost/person; ICER: $46/QALY	–	QALYs	HC; IC pub	General Australian population	Generic	Markov	EHS	20 y	No	No	Limited quality of the available evidence between intermediate outcomes and health
	45	Information campaign (FFFF) (FV)	BCC - I	Agt	0.0546 ΔQALYs/person gained; $308 Δcost/person; ICER: $5600/QALY	–										
Dodhia et al. 2012 (40), England	46	Sodium reformulation	FE - I	S-A	Three generic reformulation scenarios: 238,043 - 579,869 DALYs gained; −£1.86 to −£0.77 bil net costs; ICER: cost-saving	+	Incidence: IHD, stroke; Mortality: IHD, stroke; DALYs	HC	General English population	Generic	CRA	HS	10 y	No	No	CVD and hypertension data from 2003; non-CVD deaths not affected by the intervention; incidence, case fatality and mortality from cohort studies assumed to be transferable to the English population; assumed average effect size over time horizon; assumption that treatment with no control on hypertension would not reduce risk; effect of prevention interventions starts in the fourth year
Ha and Chisholm, 2011 (41), Vietnam	47	Information campaign and voluntary salt reformulation	BCC - I and FE - I	S-A	46,000 DALYs averted; VND89 bil net costs per year; ACER: VND1,945,002/DALY	–	Incidence: IHD, stroke; DALYs	HC; IC pub	General Vietnamese population	PopMod + WHO CHOICE syntax	Markov	GCEA	10 y	No	No	No original data on salt consumption; not all benefits of interventions considered

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Mantilla Herrera et al., 2018 (42), Australia	48	Voluntary food labeling (overall nutrient composition)	FE – N	S-A	4207 HALYs gained; A$4.5 mil net costs; ICER: A$1728/HALY	–	HALYs	HC; IC priv and pub	General Australian population	CRE- Obesity Model	MSLT	LS	L	No	No	No clear evidence on the effect of labeling on reformulation (reduced energy density); assumption that consumers do not change purchasing or eating behavior; potentially selective adaption of voluntary labeling; cohort model assumes homogeneity within age-sex groups; intervention effect may decline; potential time lag between implementation and reformulation
	49	Mandatory food labeling (overall nutrient composition)	FE - N	S-A	49,949 HALYs gained; A$197.7 mil net costs; ICER: A$4752/HALY	–										
Huang et al., 2019 (15), USA	50	Sugar labeling	FE - N	S-A	727,000 QALYs gained; –$61.92 bil net costs (S persp.); ICER: cost-saving; NMB (WTP: $100,000): $134.78	+	Incidence: CHD, stroke, T2D; Mortality: CHD, stroke, T2D; LYG; QALYs	HC; IC priv and pub; PC; ICC	General US population	IMPACT food policy	Microsimulation	EHS and S	20 y	(Y)	Yes	No causal interpretation possible; average population effects instead of individual interpretation; potential underestimation due to assumed declining added sugar consumption; inclusion of costs from competing diseases could reduce cost-effectiveness; inclusion of health benefits from reduced obesity-related cancers or dental outcomes could increase cost-effectiveness
	51	Sugar labeling and reformulation	FE - I and FE – N	S-A	1,337,000 QALYs gained; –$113.25 bil net costs (S persp.) ICER: cost-saving; NMB (WTP: $100,000): $247.03	+										
Huse et al. 2019 (43), Australia	52	Mandatory restriction on price promotions for SSBs	FE - U	S-A	34,260 HALYs gained; –A$359 mil net costs; ICER: cost-saving	+	Incidence: cancers, IHD, HHD, stroke, T2D, osteoarthritis; HALYs	HC; IC pub	General Australian population	CRE- Obesity model	MSLT	EHS	L	(Y)	No	UK estimates might not translate to Australia; potential response bias in underlying dietary data; costs to Australian consumers and industry were unavailable; real-world retailer and/ormanufacturer response to regulation is unknown; assumption of no compensatory behavior

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Jevdjevic et al., 2019 (44), Netherlands	53	SSB tax	FE - U	S-A	1,030,163 caries lesions prevented; 2.13 caries-free tooth years per person; −€159.01 mil net treatment costs	+	Caries-free tooth-years; Incidence: caries lesions	HC; IC pub; TR	General Dutch population aged 6–79 y	Generic	Markov	LS	L	(Y)	No	No country-specific price and cross-price elasticities; consumption beyond household not included; "Meal deals" could mitigate tax effect; assumption of same sensitivity to taxation across population subgroups; long-term effect of SSB tax limited; extrapolation to other countries limited
Kim et al., 2019 (45), USA	54	Excise tax on processed meat	FE - U	S-A	593,000 QALYs gained; $160 mil net costs (HS persp.); −$2732 mil net costs (S persp.); ICER (HS): $270/QALY; ICER (S): cost-saving	+/−	Incidence: cancers; Mortality: cancers; LYs; QALYs	HC; IC priv & pub; PC; TC	General US population aged ≥20 y	Dietary and Cancer Outcome Model (DICOM)	Markov	EHS & S	L	(Y)	Yes	Risk factor-disease estimates are subject to uncertainty; competing mortality risks not modeled; policy effect sizes derived from taxes on SSBs and warning labels for smoking
	55	Cancer risk labeling of processed meat	FE – N	S-A	−$1259.7 mil net costs (HS) −$4512.7 mil net costs (S); ICER (HS): cost-saving; ICER (S): cost-saving	+										
Lal et al., 2017 (46), Australia	56	SSB sales tax	FE - U	S-A	175,300 HALYs gained; −A$1733 mil net healthcare costs; ICER: cost-saving	+	HALYs	OopC; other HC; IC priv and pub; DWL; Oop tax cost; TR	General Australian population aged 2–100 y	CRE- Obesity model	MSLT	LS	L	Yes	No	Indicator of socioeconomic position (SEIFA); price elasticities for household income groups assumed to be similar to SEIFA groups; potential response bias in underlying dietary data; no cross-price elasticities of food substitutes; real-world prices of SSBs might be different; not all costs available for Australia; intervention effect on oral health not included; indirect costs (lost productivity, absenteeism, presenteeism) not included; HRQoL estimates not available for all child age groups

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Laverty et al., 2019 (47), England	57	UK responsibility deal (private-public partnership to improve population health) (salt)	FE - I	S-A	35,000/6400 additional CVD cases/deaths (probability of superiority: <0.1%); 5300/2500 additional GCa cases/deaths (probability of superiority: 5.8%); £910 mil net CVD costs; £215.4 mil net GCa costs	+	Incidence: CVD, GCa; mortality: CVD, GCa	HC; PC	General English population	IMPACT NCD	Microsimulation	S	15 y	Yes	Yes	No causal interpretation of effect (longitudinal data collection of salt intakes in the same people not available); people aged 64 or older are assumed to have similar trends in salt intake than those in HSE; limited information on the socioeconomic position of survey participants; counterfactual is linear decline in salt intake; costs estimates based on workplace productivity and not other costs including the economic value of a QALY
Lee et al., 2019 (48), USA	58	Fruit and vegetable subsidy in Medicaid and Medicare	FE - U	S-A	4.64 mil QALYs gained; $83.5 bil net costs (HS persp.); $68.8 bil net costs (S persp.) ICER (HS): $18,184/QALY; ICER (S): $14,576/QALY	–	Incidence: CVD, diabetes; Mortality: CVD; QALYs	HC; IC pub; PC; TC	US adults in Medicaid or Medicare aged 35–80 y	CVD- PREDICT	Microsimulation	EHS and S	L	(Y)	Yes	Only foods purchased at stores accepting EBT cards; no direct; causal evidence; potential over- (residual confounding) or underestimation (measurement error, regression dilution bias) of etiologic effects; health and cost outcomes from other diseases not modeled; political and legal feasibility not considered
	59	Healthy foods subsidy in Medicaid and Medicare	FE - U	S-A	8.40 mil QALYs gained; $111.1 bil net costs (HS); $80.5 bil net costs (S); ICER (HS): $13,194/QALY; ICER (S): $9497/QALY	–										
Long et al., 2015 (49), USA	60	SSB excise tax	FE - U	S-A	101,000 DALYs averted; 871,000 QALYs gained; −$23.2 mil net costs; ICERs (all outcomes): cost-saving	+	LYs; QALYs; DALYs	HC; IC priv and pub; TR	General US population aged 2–100 y	CHOICES (based on ACE- prevention)	MSLT	LS	10 y	Yes[3]	No	No direct evidence (all simulation models); limited evidence for some parameters; only BMI-mediated health and economic effects; effects of tax revenue reinvestment not included; indirect costs (productivity, absenteeism, disability early retirement, mortality) of obesity not included

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Long et al., 2019 (50), USA (Maine)	61	SSB excise tax	FE - U	S-A	3560 QALYs gained; −$74.0 mil net costs; ICER: cost-saving	+	Incidence: obesity; QALYs	HC; IC priv and pub	General Maine (US) population aged 2–100 y	CHOICES	Microsimulation	(LS)	10 y	No	No	No direct evidence (all simulation models); industry costs are assumed to be equivalent to government effort; model output requested by stakeholders was beyond scope
	62	SSB restriction in SNAP	FE - I	Str	749 QALYs gained; −$10.9 mil net cost; ICER: cost-saving	+										
Manyema et al., 2015 (51), South Africa	63	SSB tax	FE - U	S-A	Male: 2.8 mil DALYs averted; −ZAR18,590 mil net health care costs; Female: 4 mil DALYs averted; −ZAR49,569 mil net health care costs	+	Incidence: T2D; prevalence: T2D; mortality: T2D; DALYs	HC	South African adult population aged ≥15 y	ACE- prevention	MSLT	(HS)	L	(Y)	No	No South African price elasticities; no price elasticities for skim milk available; substitution effect to other sweetened drinks not modeled; same price elasticities assumed by sex, age, income category, and baseline BMI; no direct impact of sugar intake on diabetes; other causes of diabetes, complications, and associated diseases not modeled; children below 15 y not modeled; BMI trends not included and diabetes incidence assumed to be constant; large proportion of undiagnosed diabetes cases in South Africa; potential underestimation of costs and savings

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Manyema et al., 2016 (52), South Africa	64	SSB tax	FE - U	S-A	550,000 DALYs averted; −ZAR5 bil net health care costs	+	Incidence: stroke; Prevalence: stroke; Mortality: stroke; HALYs	HC	South African adult population aged ≥15 y	ACE- prevention	MSLT	HS	L	(Y)	No	Potential response bias in underlying epidemiological and cost data; no South African price elasticities (cultural context important); only proxy estimates for health care cost data; costs for other diseases, care for elderly, and taxation not accounted for; direct impact of sugar intake on stroke and other relevant diseases not modeled; substitution effect to other sweetened drinks not modeled; same price elasticities by income category assumed
Martin-Saborido et al., 2016 (53), European Union	65	Mandatory TFA labeling	FE - N	S-A	1.39 mil DALYs averted; €89,153 mil net costs; ICER: €64,363/DALY	−	DALYs	HC; IC pub; PC; ICC	General EU population	Generic	Markov	S	L	(Y)	No	Potential response bias in underlying data; CAD-related hospital discharges instead of events used in modeling; high variation in several variables across EU countries
	66	Voluntary TFA reformulation	FE - I	S-A	2.93 mil DALYs averted; −€35,603 mil net costs; ICER: cost-saving	+										
	67	Mandatory TFA limits	FE - I	Str	5.32 mil DALYs averted; −€76,478 mil costs saved; ICER: cost-saving	−										

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Mason et al. 2014 (54), Tunisia	68	Health promotion campaign (Salt)	BCC - I	Agt	1151 life-years gained; PPP$17 mil net costs	–	LYG	HC; IC priv and pub	General Tunisian population	IMPACT CHD	CRA	(LS)	10 y	No	No	Unrelated health care costs, indirect costs and tax revenue not included; methodology of cost data collection varies between countries and limits comparability; policy effectiveness based on few other observed countries; not all parameters varied in sensitivity analysis; only deterministic sensitivity analysis; CHD rates are assumed to continue for 10 y; reformulation cost estimate from manufacturers may be biased; assumed single-step change in policy; assumed demand on reformulated products remains constant
	69	Food labeling (salt)	FE - N	S-A	2272 life-years gained; −PPP$39 mil net costs	+										
	70	Mandatory salt reduction in processed foods	FE - I	Str	2272 life-years gained; −PPP$39 mil net costs	+										
	71	Health promotion campaign, food labeling, and mandatory salt reduction in processed foods	BCC - I, FE – I, and FE – N	S-A	6455 life-years gained; −PPP$235 mil net costs	+										
Syria	72	Health promotion campaign (salt)	BCC – I	Agt	5679 life-years gained; −PPP$5 mil net costs	+			General Syrian population							
	73	Food labeling (salt)	FE - N	S-A	11,192 life-years gained; −PPP$34 mil net costs	+										
	74	Mandatory salt reduction in processed foods	FE - I	Str	11,192 life-years gained; −PPP$61 mil net costs	+										
	75	Health promotion campaign, food labeling, and mandatory salt reduction in processed foods	BCC - I, FE – I, and FE - N	S-A	31,674 life-years gained; −PPP$39 mil net costs	+										
Palestine	76	Health promotion campaign (salt)	BCC - I	Agt	479 life-years gained; −PPP$7 mil net costs	+			General Palestinian population							
	77	Food labeling (salt)	FE - N	S-A	945 life-years gained; −PPP$9 mil net costs	+										
	78	Mandatory salt reduction in processed foods	FE - I	Str	945 life-years gained; PPP$0.13 mil net costs	–										
	79	Health promotion campaign, food labeling, and mandatory salt reduction in processed foods	BCC - I, FE – I, and FE – N	S-A	2,682 life-years gained; −PPP$6 mil net costs	+										
Turkey	80	Health promotion campaign (salt)	BCC - I	Agt	68,816 life-years gained; −PPP$949 mil net costs	+			General Turkish population							
	81	Food labeling (salt)	FE - N	S-A	135,221 life-years gained; −PPP$1043 mil net costs	+										
	82	Mandatory salt reduction in processed foods	FE - I	Str	135,221 life-years gained; −PPP$965 mil net costs	+										

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
	83	Health promotion campaign, food labeling, and mandatory salt reduction in processed foods	BCC - I, FE – I, and FE – N	S-A	199,303 life-years gained; −PPP$1324 mil net costs	+										
Mekonnen et al., 2013 (55), USA (CA)	84	SSB tax	FE - U	S-A	10% reduction in SSB consumption: 6000 fewer CHD cases; 2700 fewer MI cases; 1600 fewer all-cause deaths; −$873 mil net diabetes and CHD costs	+	Incidence: CHD, diabetes; Mortality: CHD, AC; Total cases: MI	HC	General Californian population	CVD policy model - CA	Markov	(HS)	10 y	Yes	No	No direct evidence (all simulation models); effect measures based on published analyses of observational studies potentially subject to residual or unmeasured confounding; real-world consumer behavior different; potential response bias in underlying dietary data; did not account for artificially sweetened beverage consumption and disease risk; lost productivity not accounted for; children and adolescents not included
Mozaffarian et al., 2018 (56), USA	85	Fruit and vegetable subsidy	FE - U	S-A	20 years: 155,792 QALYs gained; −$6.69 bil net costs (S persp.); $29.66 bil food subsidy costs (G); ICER (S): cost-saving; ICER (G): $168,455/QALY	+/−	Incidence: diabetes, CVD; Mortality: CVD; QALYs	HC; IC pub	US population aged 35–80 y participating in SNAP	CVD- PREDICT	Microsimulation	EHS and G	L	(Y)	Yes	No causal interpretation possible; potential long-term change in effect; CVD risk calculations do not incorporate ethnicity; indirect costs (lost productivity) not included
	86	Fruit and vegetable subsidy and SSB restriction	FE - U and FE - I	S-A	20 years: 457,184 QALYs gained; −$17.60 bil net costs (S); $29.69 bil food subsidy costs (G); ICER (S): cost-saving; ICER (G): 26,435/QALY	+/−										
	87	Incentive/ disincentive program (SNAP-plus) (healthy and unhealthy foods)	FE - U	S-A	20 years: 551,824 QALYs gained; −$19.61 bil net costs (S); −$15.0 bil food subsidy costs (G); ICER (S): cost-saving; ICER (G): cost-saving	+										

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Nghiem et al., 2015 (57), New Zealand	88	Voluntary sodium reformulation and labeling (Tick Programme)	FE - N	S-A	7900 QALYs gained; −$34 mil net costs; ICER: cost-saving	+	Mortality rate: CVD; QALYs	HC; IC priv and pub	General New Zealand population aged ≥35 y	BODE[3]	Markov	LS	L	Yes	Yes	Structural model uncertainty not assessed; potential response bias in underlying data and intervention effects; public, consumer, and industry responses to policies unknown; no full societal perspective
	89	Mandatory sodium reformulation (breads, processed meats and sauces)	FE – I	Str	61,700 QALYs gained; −$340 mil net costs; ICER: cost-saving	+		HC; IC pub				EHS				
	90	Mandatory sodium reformulation	FE – I	Str	110,000 QALYs gained; −$600 mil net costs; ICER: cost-saving	+										
	91	Health promotion campaign, voluntary sodium reformulation and sodium labeling (sodium)	BCC - I, FE – I, and FE – N	S-A	85,100 QALYs gained; −$440 mil net costs; ICER: cost-saving	+		HC; IC priv and pub				LS				
	92	Health promotion campaign (salt)	BCC - I	Agt	25,200 QALYs gained; −$120 mil net costs; ICER: cost-saving	+										
	93	Sodium tax	FE - U	S-A	195,000 QALYs gained; −$1000 mil net costs; ICER: cost-saving	+		HC; IC pub				EHS				
	94	Salt market restriction ("sinking lid") (sodium)	FE - I	Str	211,000 QALYs gained; −$1110 mil net costs; ICER: cost-saving	+										
Nghiem et al. 2016 (58), New Zealand	95	Sodium substitution (processed foods)	FE - I	Str	294,000 QALYs gained; −$1500 mil net costs; ICER: cost-saving	+	QALYs	HC; IC pub	General New Zealand population aged ≥35 y	BODE[3]	Markov	EHS	L	Yes	Yes	Structural model uncertainty not assessed; not all potentially relevant diseases modeled; minimum risk exposure level of sodium is still debated; potential response bias in underlying data; sodium reduction might impact palatability and thus lead to more added sugar by industry or salt at the table

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
	96	Sodium substitution (low-level) (processed foods)	FE - I	Str	121,000 QALYs gained; −$620 mil net costs; ICER: cost-saving	+										
	97	Mandatory sodium reformulation (breads)	FE - I	Str	43,500 QALYs gained; −$220 mil net costs; ICER: cost-saving	+										
	98	Mandatory sodium reformulation (low-level) (breads)	FE – I	Str	15,600 QALYs gained; −$83 mil net costs; ICER: cost-saving	+										
Nomaguchi et al., 2017 (59), Australia	99	SSB tax	FE - U	S-A	63,000 DALYs gained; $2347 mil net economic gain (HCA); $1748 mil net economic gain (FCA 3 months)	+	Prevalence: obesity; LYs; DALYs	HC; PC (unpaid and paid)	General Australian population aged ≥20 y	Generic (based on ACE- prevention)	MSLT	S	L	No	No	Potential information bias in underlying data; comorbidities are assumed to be random, instead of clustered in high-risk individuals; epidemiological and cost parameters are assumed to remain stable into the future; equity impacts not analyzed; wages remain unaffected by labor supply changes; productivity effects not adjusted for potential confounders like education or income level; disease frequency data from 2003
Pearson- Stuttard et al., 2017 (60), England and Wales	100	Ban on TFAs in processed foods	FE - I	Str	Equal intake across SEC: 13,600 life-years gained; 4000 hospital admissions averted; ICER: £3100/LYG; unequal intake across SEC: 15,400 LYG; 4400 hospital admissions averted; ICER: £2700/LYG	–	Mortality: CHD; LYG; QALYs; health care utilization: CHD hospital admissions	HC; IC priv and pub; PC	General adult English and Welsh population	IMPACTecon	CRA	S	10 y	Yes	Yes	Area-based measure of deprivation; model assumes immediate health benefits; ruminant and industrial TFAs are assumed to be equally associated with mortality; estimates for reformulation costs have high variation

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
	101	Ban on TFAs	FE - I	Str	Equal intake across SEC: 27,200 LYG; 8000 hospital admissions averted; ICER: £1600/LYG; unequal intake across SEC: 29,000 LYG; 8400 hospital admissions averted; ICER: £1400/LYG	–										
Pearson- Stuttard et al., 2018 (61), USA	102	Voluntary sodium reformulation	FE - I	S-A	0.69 mil QALYs gained; −$9.7 bil net costs (health care); −$12 bil net costs (societal); ICER: cost-saving; NMB (WTP: $100,000): $81 bil	+	Mortality: AC; CHD, stroke, Incidence: CHD, stroke; LYG; QALYs	HC; IC priv and pub; PC	General US adult population aged 30–84 y	IMPACT food policy	Microsimulation	HS and S	20 y	Yes[4]	Yes	Potential information bias in underlying data; decline in sodium trends assumed to continue; only disease mediated through blood pressure evaluated; additional potential benefit through increased potassium intake not modeled; unrelated medical costs not included
Rubinstein et al., 2009 (62), Argentina (Buenos Aires)	103	Health promotion campaign (healthy foods, salt and fat)	BCC - I	Agt	1158 DALYs averted per year; ARS$634,000 total costs per year; ICER: ARS$547/DALY	–	DALYs	PLC; IC	General population of Buenos Aires	PopMod	Markov	GCEA	10 y	No	No	Not reported
	104	Voluntary salt reformulation (breads)	FE - I	S-A	579 DALYs averted per year; ARS$87,000 total costs per year; ICER: ARS$151/DALY	–										

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TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Rubinstein et al., 2010 (63), Argentina	105	Voluntary salt reformulation (breads)	FE - I	S-A	672.80 DALYs averted; −I$947,581 net costs; ICER: cost-saving	+	DALYs	HC; IC pub	General Argentinian population aged ≥35 y	Generic	CRA	EHS	5 y	(Y)	No	Only risk factors with available data from the underlying survey could be included; data on risk factor prevalence were categorical or dichotomous, prohibiting a continuous estimation; limited scope of interventions; no direct evidence (all simulation models); not all input parameters were country specific
Rubinstein et al., 2015 (64), Argentina	106	Mandatory TFA reformulation	FE - I	Str	5237 DALYs averted; −$17.3 mil net costs	+	Mortality: CHD, MI; Incidence: CHD; DALYs	HC; IC pub	General Argentinian population aged ≥35 y	Generic	—	EHS	10 y	(Y)	No	CHD risk based on old equations; global estimates used to adjust for underreporting of CHD; industry reformulation costs not included; no precise data on baseline TFA intake
Sacks et al., 2011 (65), Australia	107	Food labeling (overall nutrient composition)	FE - N	S-A	45,100 DALYs averted; A$455 mil total cost offsets; gross ICER: A$1800/DALY; net ICER: cost-saving	+/−	DALYs	HC; IC priv and pub	Australian adults aged ≥20 y	ACE- prevention	MSLT	LS	L	(Y)	No	Direct evidence of intervention impact relatively weak; analyses conducted on the food category rather than on the product level
	108	Junk food tax (snacks/sweets and SSBs)	FE - U	S-A	559,000 DALYs averted; A$5550 mil total cost offsets; gross ICER: $30/DALY; net ICER: cost-saving	+/−										

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Salomon et al., 2012 (66), Mexico	109	Voluntary salt reformulation	FE - I	S-A	19,000 DALYs averted per year; I$11 mil net annual cost; ICER: $570/DALY	–	DALYs	PLC; IC	General Mexican population	PopMod	Markov	GCEA	100 y	No	No	Potential bias due to extrapolation of evidence and assumptions from other countries; no exhaustive details on uncertainty around point estimates or parameter values and assumptions
	110	Mandatory salt reformulation	FE - I	Str	37,000 DALYs averted per year; I$11 mil net annual cost; ICER: $293/DALY	–										
	111	Health promotion campaign (cholesterol and energy intake)	BCC – I	Agt	38,000 DALYs averted per year; I$22 mil net annual cost; ICER: $567/DALY	–										
Sánchez- Romero et al., 2016 (67), Mexico	112	SSB tax	FE - U	S-A	66,000 cases of diabetes prev.; 5100 cases of CHD prevented; 1800 cases of stroke prevented; 4200 fewer all-cause deaths prev.; −I$483 mil net diabetes health care costs	+	Incidence: diabetes, CHD, stroke; Mortality: CHD, stroke, AC; Total cases: MI	HC	General Mexican population aged 35–94 y	CVD policy model - Mexico	Markov	(HS)	10 y	(Y)	Yes	Reliance on US input parameters where Mexico-specific data were lacking; limited data on health care costs other than those related to diabetes; lack of information on long-term SSB price elasticities that are specific to subgroups
Saxena et al., 2019a (68), South Africa	113	SSB tax	FE - U	S-A	7898 T2D deaths avoided; −ZAR1,701.1 mil net costs; ZAR5,490 mil annual tax revenue; 12,179 cases of poverty avoided; 32,377 cases of catastrophic expenditure averted	+	Mortality: T2D	OopC; PC; HC; TR; CHE	General South African population	ACE- prevention	MSLT	(S)	20 y	Yes	No	No direct estimates for the price elasticities of SSB consumption by income; no substitution effects to other drinks or complementary foods considered; only T2D-related mortality; indirect costs did not account for labor force dropout, premature mortality, or others; no subgroup effects for race, sex, and age modeled (only population average)

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Saxena et al., 2019b (69), Philippines	114	SSB tax	FE - U	S-A	5913 T2DM deaths avoided; 10,339 IHD deaths avoided; 7950 stroke deaths avoided; −P31.6 bil net health care costs; −P18.6 bil out-of-pocket costs; P41 bil annual tax revenue; 13,890 cases of catastrophic expenditure averted	+	Mortality: diabetes, IHD, stroke; Incidence: diabetes, IHD, stroke	OopC; HC; TR; CHE	General Filipino population	ACE- prevention	MSLT	(LS)	20 y	Yes	No	No direct estimates for the price elasticities of SSB consumption by income; no substitution effects to other foods considered (cross-price elasticities); no data on composition of all SSBs; potential reformulation due to 2-tier tax structure not modeled; no subgroup data on health care use and disease conditions; inpatient costs instead of primary care costs; nonmedical costs not considered (lost productivity, transportation, caregiver)
Schwendicke et al., 2016 (70), Germany	115	SSB tax	FE - U	S-A	750,000 less caries teeth; −€80 mil net costs; €37.99 bil tax revenue	+	Incidence: caries	HC; TR	General German population aged 14–79 y	Generic	Microsimulation	HS	10 y	Yes	No	Potential information bias in underlying data; data from before 2009; increasing consumption of SSBs (especially in low-income groups) not accounted for; no German, age-dependent elasticities; substitution to sugary foods was not modeled; long-term costs higher (re-interventions); no implementation and administration cost

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Smith-Spangler et al., 2010 (71), USA	116	Voluntary sodium reformulation	FE - I	S-A	2,060,790 QALYs gained; −$32.1 bil net costs	+	Incidence: MI, stroke; LYs; QALY	HC; P-PCC	General US population aged 40–85 y	Generic	Markov	LS	L	(Y)	Yes	Intervention might produce unpredictable dietary changes (e.g., substitution); potential unintended consequences of modest sodium reduction not included; cost-savings not from all relevant diseases included; minority populations underrepresented in cardiovascular risk equations
	117	Sodium tax (processed foods)	FE - U	S-A	1,313,304 QALYs gained; −$22.4 bil net costs	+										
Sowa et al., 2019 (72), Australia	118	SSB tax	FE - U	S-A	3.89 mil less DMFT; −A$666 mil net costs	+	Incidence: DMFT	HC	General Australian adult population	Generic	(Markov)	HS	10 y	No	No	No direct evidence; potential unpredictable substitution effects in industry and individual responses; market distortions and potential deadweight loss may be very high
Veerman et al., 2016 (73), Australia	119	SSB tax	FE - U	S-A	167,993 DALYs averted; −A$581.4 mil net costs; A$400 mil tax revenue per year	+	Prevalence/ incidence/ mortality: obesity, IHD, HHD, stroke, T2D, osteoarthritis, cancers; HALYs; DALYs	HC; IC pub; TR	Australian adults aged ≥20 y	ACE- prevention	MSLT	EHS	L	No	No	Potential information bias in the underlying data; impact on different socioeconomic groups not modeled
Wang et al., 2012 (74), USA	120	SSB tax	FE - U	S-A	2,377,000 less diabetes person-years; 95,000 cases of CHD prevented; 30,000 cases of MI prevented; 8000 cases of stroke prevented; 26,000 deaths prevented; −$17.1 bil net costs	+	Diabetes PY; Incidence: CHD; Total cases: MI, stroke; Mortality: AC	HC; TR	General US adult population aged 25–64 y	CVD policy model - USA	Markov	HS	10 y	(Y)	Yes	Potential information bias in the underlying data; not all relevant diseases included; empirical evidence for some key assumptions still inconclusive (industry response, consumer behavior, substitution effects)

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Wang et al., 2016 (75), China	121	Health promotion salt campaign (cooking education)	BCC - I	Agt	401,000 QALYs gained; −I$1,406 mil net CVD health care costs per year	+	Incidence: CVD; Mortality: CVD; QALYs	HC	General Chinese adult population aged 35–94 y	CVD policy model - China	Markov	HS	10 y	(Y)	Yes	Potential bias due to data inputs from diverse studies; salt-related change in blood pressure based on study including normo- and hypertensive patients and long-term follow-up unclear; implementation costs and potential costs of adverse effects not included
	122	Health promotion campaign (sodium substitution)	BCC - I	S-A	1,185,000 QALYs gained; −I$4,126 mil net CVD health care costs per year	+										
Wilcox et al., 2014 (76), Syria	123	Health promotion campaign (salt)	BCC - I	Agt	5679 LYG; −PPP$5,346,438 net costs; ICER: cost-saving	+	LYG	HC; IC priv and pub	Syrian adult population aged ≥25 y	IMPACT CHD - Syria	CRA	(LS)	10 y	No	Yes	Incomplete data for target population; dietary salt intake and intervention effectiveness data (potentially large cultural heterogeneity) extracted from other countries; no data on productivity loss associated with CHD; CHD rates assumed to persist for 10 y
	124	Salt labeling	FE - N	S-A	11,192 LYG; −PPP$34,952,472 net costs; ICER: cost-saving	+										
	125	Salt reformulation	FE - I	Str	11,192 LYG; PPP$61,032,931 net costs; ICER: PPP$5,453/LYG	-										
	126	Health promotion campaign, salt reformulation, and salt labeling	BCC - I, FE - I, and FE - N	S-A	31,674 LYG; −PPP$39,190,619 net costs; ICER: cost-saving	+										
Wilde et al., 2019 (77), USA	127	SSB tax	FE - U	S-A	0.0201 ΔQALYs/person gained; −$270 Δcosts/person cost (HS); −$43.16 bil net costs (S); ICER (HS): cost-saving; ICER (S): cost-saving	+	Total cases: MI, IHD; Mortality: stroke, IHD; LE; QALYs	HC; IC priv and pub; TR	General US population aged 35–85 y	CVD- PREDICT	Microsimulation	HS, S and SH	L	No	Yes	Not all relevant diseases attributable to SSB intake modeled; indirect costs (lost productivity) not included; children and adolescents not included; time lags of effect could be longer than assumed (1 y); modeling of industry profit function not attempted; no specific replacement scenarios modeled

(*Continued*)

TABLE 1 (*Continued*)

Study, year, country	No.	Policy (details)	NOURISHING	S-A	Cost-effectiveness results	CS?	Health outcomes	Cost outcomes	Population	Model name	Method	Cost persp.	Time horizon	EQ[2]	VD	Key authors' limitations
Wilson et al., 2016 (78), New Zealand	128	Mandatory sodium reformulation (all packaged foods, fast food/ restaurants, and discretionary use)	FE – I	S-A	235,000 QALYs gained; −NZ$1260 mil net health system costs; ICER: cost-saving	+	QALYs	HC; IC pub	General New Zealand population aged ≥35 y	BODE[3]	Markov	EHS	L	Yes	Yes	No direct evidence; structural model uncertainty not assessed; not all potentially relevant diseases modeled; potential bias in underlying data and intervention effects; public, consumer, and industry responses to policies unknown
	129	Reformulation (packaged foods)	FE - I	Str	122,000 QALYs gained; −NZ$660 mil health system costs; ICER: cost-saving	+										
	130	Mandatory sodium reformulation (breads)	FE - I	Str	8900 QALYs gained; −NZ$45.2 mil health system costs; ICER: cost-saving	+										
	131	Mandatory sodium reformulation (processed meats)	FE - I	Str	13,400 QALYs gained; −NZ$70 mil health system costs; ICER: cost-saving	+										
	132	Mandatory sodium reformulation (sauces)	FE - I	Str	20,000 QALYs gained; −NZ$106 mil health system costs; ICER: cost-saving	+										
	133	Mandatory sodium reformulation (snack foods)	FE - I	Str	6,100 QALYs gained; −NZ$30.3 mil health system costs; ICER: cost-saving	+										
	134	Mandatory sodium reformulation (All bakery products)	FE - I	Str	20,400 QALYs gained; −NZ$108 mil health system costs; ICER: cost-saving	+										
	135	Mandatory sodium reformulation (cheese)	FE - I	Str	8800 QALYs gained; −NZ$44.6 mil health system costs; ICER: cost-saving	+										
	136	Mandatory sodium reformulation (fast food/restaurants)	FE - I	Str	68,700 QALYs gained; −NZ$370 mil health system costs; ICER: cost-saving	+										

[1] AC, all-cause; ACE, Assessing Cost-Effectiveness; ACER, average cost-effectiveness ratio; Agt, agentic; BCC-I, Behavior Change Communication; bil, billion; CHD, coronary heart disease; CHE, catastrophic health expenditure; CRA, Comparative risk assessment; CS?, Cost-saving?; DMFT, decayed, missing, or filled teeth; DWL, deadweight loss; EHS, extended health care sector; EQ, equity analysis; FCA, friction cost approach; FE - I, food environment–food supply chain; FE - N, food environment–food labels; FE - U, food environment–economic tools; FV, fruit and vegetables; G, government; GCa, gastric cancer; GCEA, generalized cost-effectiveness analysis; HALY, health-adjusted life-year; HC, health care cost; HCA, human capital approach; HHD, hypertensive heart disease; HRQoL, health-related quality of life; HS, health sector; IC, implementation cost; ICC, informal care cost; ICER, incremental cost-effectiveness ratio; IHD, ischemic heart disease; L, lifetime; LE, life expectancy; LS, limited societal; LY, life-year; LYG, life-years gained; MI, myocardial infarction; mil, million; MSLT, proportional Markov multistate life table; NHS, National Health Service; NMB, net monetary benefit; OopC, out-of-pocket cost; PC, productivity cost; persp., perspective; PLC, patient-level cost; P-PCC, public-private collaboration cost; priv, private sector; pub, public sector; PY, person-years; QALY, quality-adjusted life-year; S, societal; S-A, structural-agentic; SH, stakeholders; SNAP, Supplemental Nutritional Assistance Program; SSB, sugar-sweetened beverage; Str, structural; TC, time cost; TFA, *trans* fatty acid; TR, tax revenue; VD, validation information; WTP, willingness-to-pay.

[2] Extent of equity analysis: Yes, formal equity analysis; No, no equity analysis; (Y), only health outcomes stratification.

[3] Only qualitative equity analysis.

[4] Subgroups are analyzed and reported but equity implications are only mentioned in the Discussion section.

components of an economic evaluation depending on the relevant stakeholders and payers.

Due to inconsistencies in reporting and definitions, we re-defined the costing perspective for each study according to the following hierarchy. Studies including only health sector costs were assigned a "health sector" perspective. Studies additionally including public sector policy implementation costs were assigned an "extended health sector" perspective. Studies further including private sector policy implementation costs were assigned a "limited societal" perspective, and finally, studies also including productivity costs were assigned a (full) "societal" perspective. All costing perspectives include the cost components of the respective less-extensive perspective.

To be consistent, we defined savings as negative costs, reported net costs where possible, and did not report the numerical value of negative incremental cost-effectiveness ratios (ICERs). The ICER is a measure combining incremental health gains with incremental costs [e.g., additional cost per quality-adjusted life-year (QALY) gained] that has no meaningful interpretation below zero (79).

We also classified policies according to NOURISHING, a framework from the World Cancer Research Fund providing global-level recommendations for dietary policy, and categorized them based on a definition from McLaren et al. (80) according to which population-based policies can fall on a continuum from agency (referring to individual ability to make the choice to act) to structure (referring to institutions and norms that shape individual behavior).

Finally, we indicated whether validation information was available for studies, which was defined as information about any type of conceptual, computer implementation, or internal or external operational validation procedure, as defined by the Assessment of the Validation Status of Health-Economic decision models tool (81).

Critical appraisal

We deviated from our protocol and—although not considered essential for scoping reviews—undertook a quality appraisal of the included modeling studies. We extended the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) checklist for the adequate reporting of economic evaluations (82) based on recent recommendations made by the Second Panel on Cost-Effectiveness in Health and Medicine (83) and a checklist developed for the quality assessment of nutrition simulation models (84). The revised checklist contains a total of 31 items that were rated as fulfilled, partially fulfilled, or not fulfilled (**Supplemental Methods 4**).

Synthesis

Results were synthesized in narrative, tabular, and graphical mapping formats. We summarized studies according to publication year, country, quality, model types, modeled risk factor–outcome pathways, model validation information and uncertainty, reported health, cost and cost-effectiveness outcomes, and limitations reported by authors. We summarized model applications according to policy types and nutritional targets.

To visualize the results of the mapping, we used circos (**Figure 2**), alluvial (**Figure 3**), and bar (**Figures 4** and **5**) plots. Circos plots enable the visual representation of conditional frequencies of variables. In our case, the application frequency of nutritional targets can be analyzed conditional on policy and model type. Alluvial plots follow a similar rationale and are chosen here to intuitively visualize the frequency with which risk factor to outcome pathways have been modeled.

Results

A description of the included modeling studies and model applications in the first stage is given in Table 1. Additional information is available in Supplemental Tables 1 and 2.

Flow diagram

We identified 9171 records, of which 6845 remained after de-duplication. Of 6845 titles and abstracts screened, 131 articles were assessed, and 54 subsequently deemed eligible. Finally, through backward and forward citation searching, 22 additional articles were identified of which 2 were eligible and 20 classified as supporting documents (Figure 1). In total, we included 56 modeling studies performing an economic evaluation of dietary policies, which contained 136 model applications after disaggregation.

General information

Of the 56 modeling studies included in the first stage, 88% were published after 2010, with a clustering of studies after 2015 and 15 studies published very recently in 2019 (**Supplemental Figure 1**).

Fourteen studies modeled dietary policy in Australia (30, 33–36, 38, 39, 42, 43, 46, 59, 65, 72, 73); 14 in the United States (15, 16, 28, 31, 45, 48–50, 55, 56, 61, 71, 74, 77); 6 in England (14, 26, 27, 37, 40, 47); 4 each in South Africa (14, 51, 52, 68), New Zealand (32, 57, 58, 78), and Mexico (14, 29, 66, 67); 3 in Argentina (62–64); 2 each in Syria (54, 76) and China (14, 75); and a single study each in Vietnam (41), Turkey (54), Tunisia (54), Russia (14), the Netherlands (44), the Philippines (69), Palestine (54), India (14), Germany (70), the European Union (53), England and Wales combined (60), and Brazil (14). Two of the US studies were from single states, one from Maine (50) and one from California (55). One study from Argentina involved only the city of Buenos Aires (62).

Quality appraisal

Approximately half of the studies (29/56) fulfilled 90% or more of all quality criteria on our checklist at least partially. Across all studies, model validation (item 22), transparency reporting (item 23), and characterization of heterogeneity (item 27) were the least reported items. Beyond these, the primary reasons some studies achieved less than the aforementioned threshold were an incomplete description of the event pathway (item 18), not defining the software

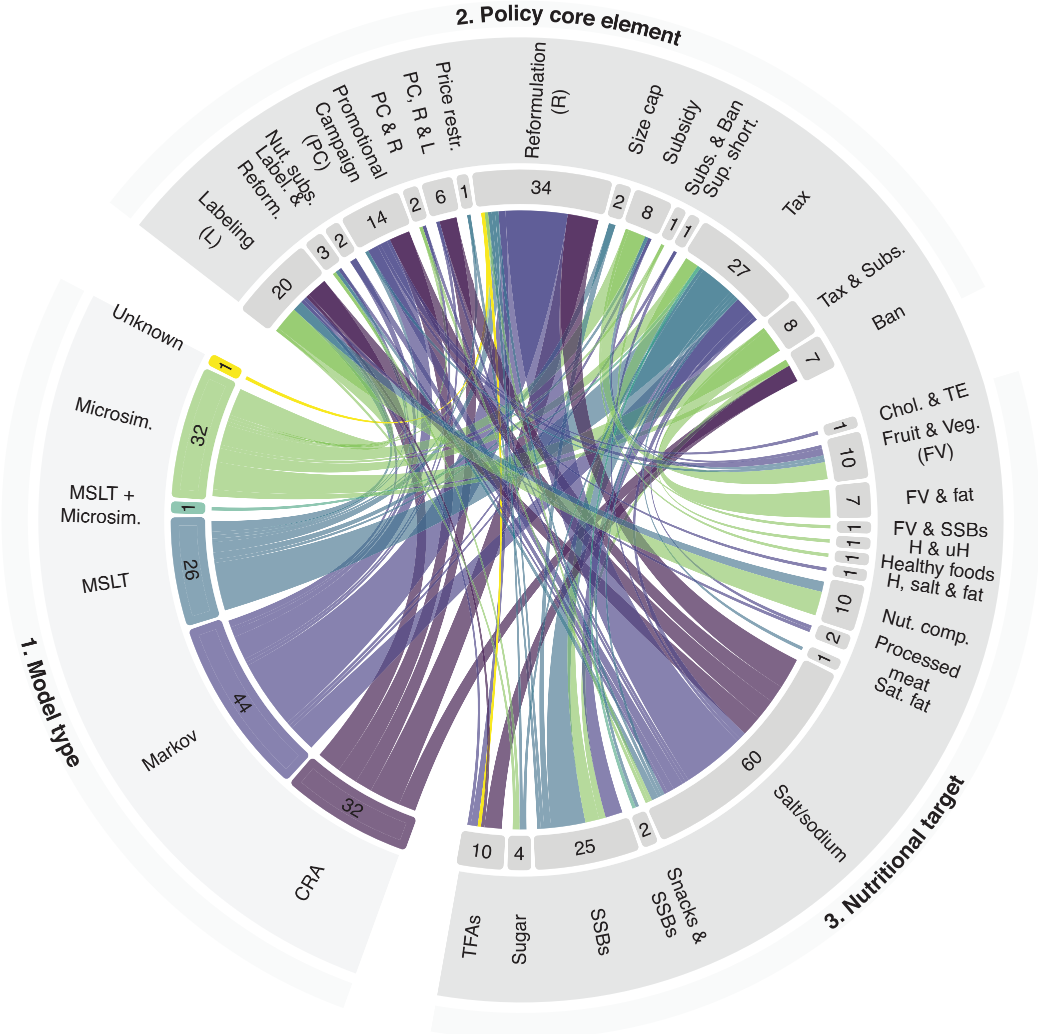

FIGURE 2 Circos plot of model application frequency by model type, policy core element, and nutritional target. $n = 136$ applications from 56 modeling studies. Color represents model type. First (outermost) circle: variable name; second circle: variable level; third circle: application frequency. Chol, cholesterol; CRA, comparative risk assessment; FV, fruit and vegetables; H, healthy foods; L, labeling; Microsim, microsimulation; MSLT, proportional Markov multistate life table; Nut comp, overall nutrient composition; Nut subs, Nutrient substitution; PC, promotional campaign; Price restr, price restriction; R, reformulation; Sat fat, saturated fat; SSB, sugar-sweetened beverage; Subs, subsidy; Sup short, supply shortage; TE, total energy intake; TFA, *trans* fatty acid; uH, unhealthy foods.

used to implement the model (item 19), nondisclosure of conflicts of interest (item 31), and not identifying the study as an economic evaluation in the title (item 1) (**Supplemental Table 3**).

Dietary policies

Across all 136 model applications, at the most granular level, 78 unique policies (e.g., cancer risk labeling of processed meats, "2 fruit 5 veg every day" campaign) were evaluated. We clustered these (post hoc) into 15 broader policy types based on core policy mechanisms (Table 1 and Figure 2), comprising the following concepts and their combinations: reformulation ($n = 33$ applications); tax ($n = 27$); labeling ($n = 20$); promotion campaign ($n = 14$); subsidy (including incentive policies) ($n = 8$); tax and subsidy ($n = 8$); total ban ($n = 7$); promotion campaign, labeling, and reformulation ($n = 6$); labeling and reformulation ($n = 3$); promotion campaign and reformulation ($n = 2$); nutrient substitution ($n = 2$); size cap ($n = 2$); promotion restriction ($n = 1$); subsidy and total ban ($n = 1$); and supply shortage ($n = 1$).

Nutritional targets

Overall, 29 unique nutrients, food groups, or their combinations were targeted by policies. We broke these down into 15 core nutritional categories, which reflect key policy targets analyzed in the included studies. By this means, we reduced the number of categories but still ensured that similar nutrients or food groups addressed using distinct types of

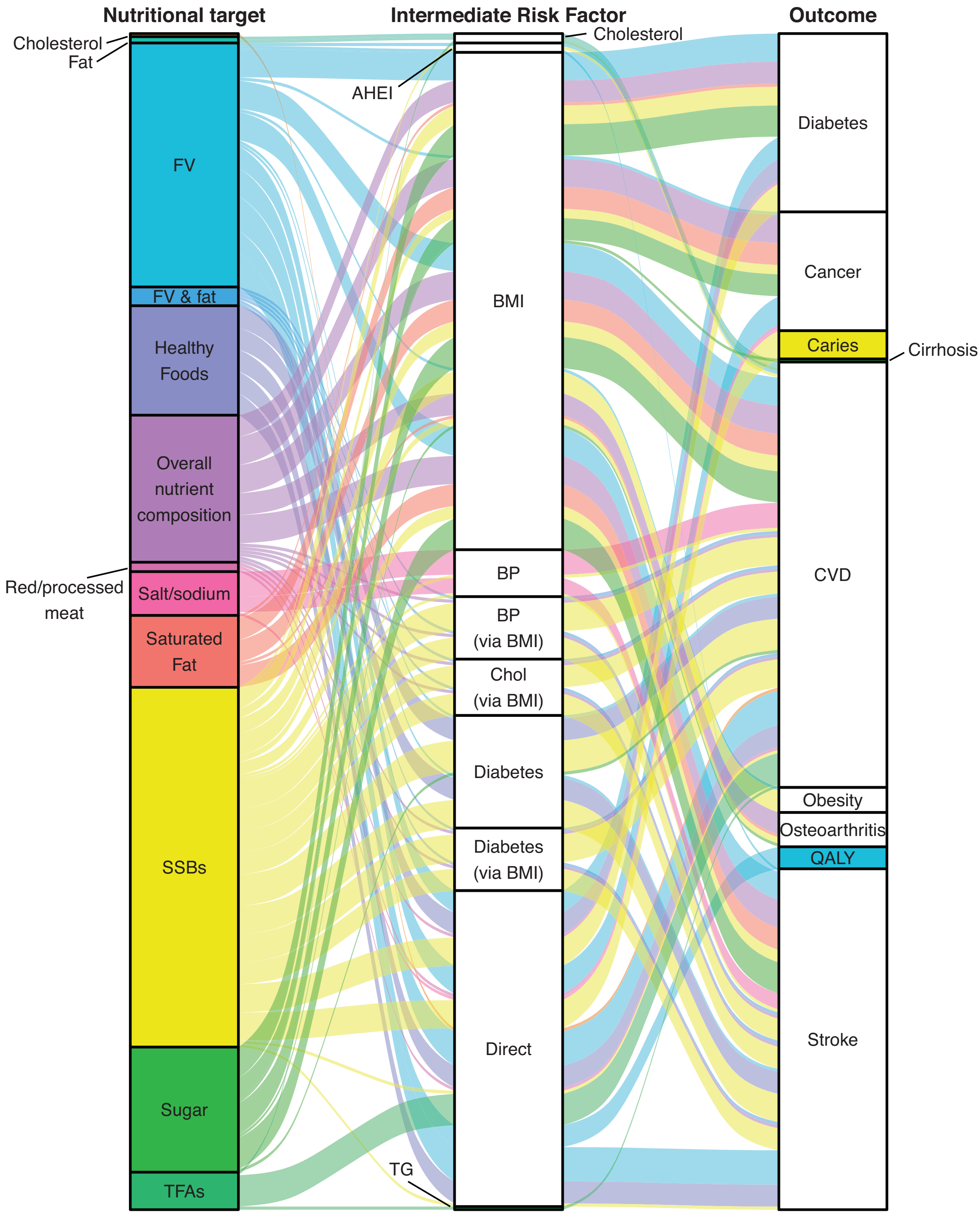

FIGURE 3 Alluvial plot of implemented diet, risk factor, and outcome pathways across all studies. Reading from left to right. Based on 56 modeling studies. The number of modeled pathways per study varies. Vertical axis (number of pathways) not shown. Color coding of outcomes shows exclusive pathways. AHEI, Alternative Healthy Eating Index; BP, blood pressure; Chol, cholesterol; CVD, cardiovascular disease; FV, fruit and vegetables; QALY, quality-adjusted life-year; SSB, sugar-sweetened beverage; TFA, *trans* fatty acid; TG, triglycerides.

policies were separated. These categories were (combinations are disaggregated): salt/sodium ($n = 61$ applications), sugar-sweetened beverages (SSBs) ($n = 31$), fruit and vegetables ($n = 15$), TFAs ($n = 10$), overall nutrient composition ($n = 10$), fat ($n = 8$), sugar ($n = 4$), healthy foods ($n = 3$), processed meat ($n = 2$), snacks and sweets ($n = 2$), saturated fat ($n = 1$), cholesterol ($n = 1$), unhealthy foods ($n = 1$), and energy intake ($n = 1$) (Figure 2).

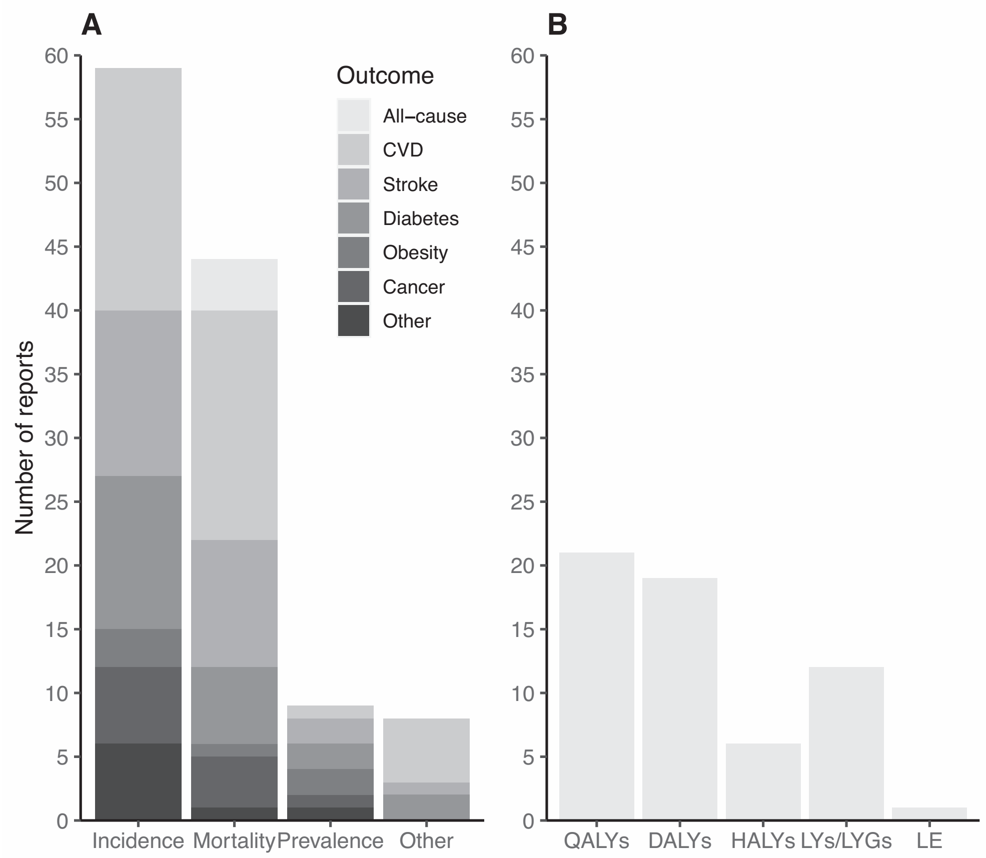

FIGURE 4 Bar plot of number of studies reporting different types of population health metrics by outcome category. (A) Frequency of reported epidemiological metrics by metric type and outcome based on 56 modeling studies. A single study may report multiple incidence, prevalence, or mortality values. (B) Frequency of reported types of adjusted or unadjusted life-year–based metrics based on 56 modeling studies. CVD, cardiovascular disease; DALY, disability-adjusted life-year; HALY, health-adjusted life-year; LE, life expectancy; LY, life-year; LYG, life-year gained; QALY, quality-adjusted life-year.

Few model applications (23/136) evaluated policies that were specifically restricted to subgroups such as sodium in breads, processed meats, and sauces [e.g., Nghiem et al. (57)].

When analyzing the combination of policy types and nutritional targets, some patterns emerged. First, economic evaluations of policies aiming to reduce SSB intake mainly focused on taxes (Figure 2). Very few evaluated other SSB policy types such as serving-size caps. Second, economic evaluations of salt/sodium and TFA policies focused almost exclusively on 2 types of strategies: structural policies such as reformulation or total bans and predominantly agentic policies such as labeling (Figure 2). Third, the evaluated policies that addressed an insufficient intake of fruit and vegetables were either promotional campaigns or subsidy policies, sometimes combined with a tax on other unhealthy nutrients and food groups (Figure 2 and Table 1).

Model types

We identified 4 major types of simulation models used for the economic evaluation of population-based policies addressing these nutritional targets (Table 1). Markov cohort models combined with a proportional multistate life table were the most popular approach used in 18 studies. Seventeen studies used standard Markov cohort models, 11 studies applied microsimulation, and 7 studies used CRA methods. In addition, 1 study used results from a Markov multistate life table approach as inputs for a microsimulation. For 1 study, the model type was unknown.

Figure 2 visualizes patterns of model type, policies, and nutritional targets. Starting at the bottom left and following the respective color code of each model type, the circos plot displays the application frequency with which, for example, Markov models (blue-gray) have been used to evaluate taxes (upper right side), which addressed SSBs (bottom).

CRA (purple) and Markov cohort models (blue-gray) have mainly been used to evaluate salt/sodium or TFAs using reformulation, labeling, or promotional campaign policies, including their combinations. Markov multistate life table models (turquoise) were primarily used for SSB taxes and reformulation strategies. Microsimulations (green) were regularly applied to more complex policies (e.g., tax and

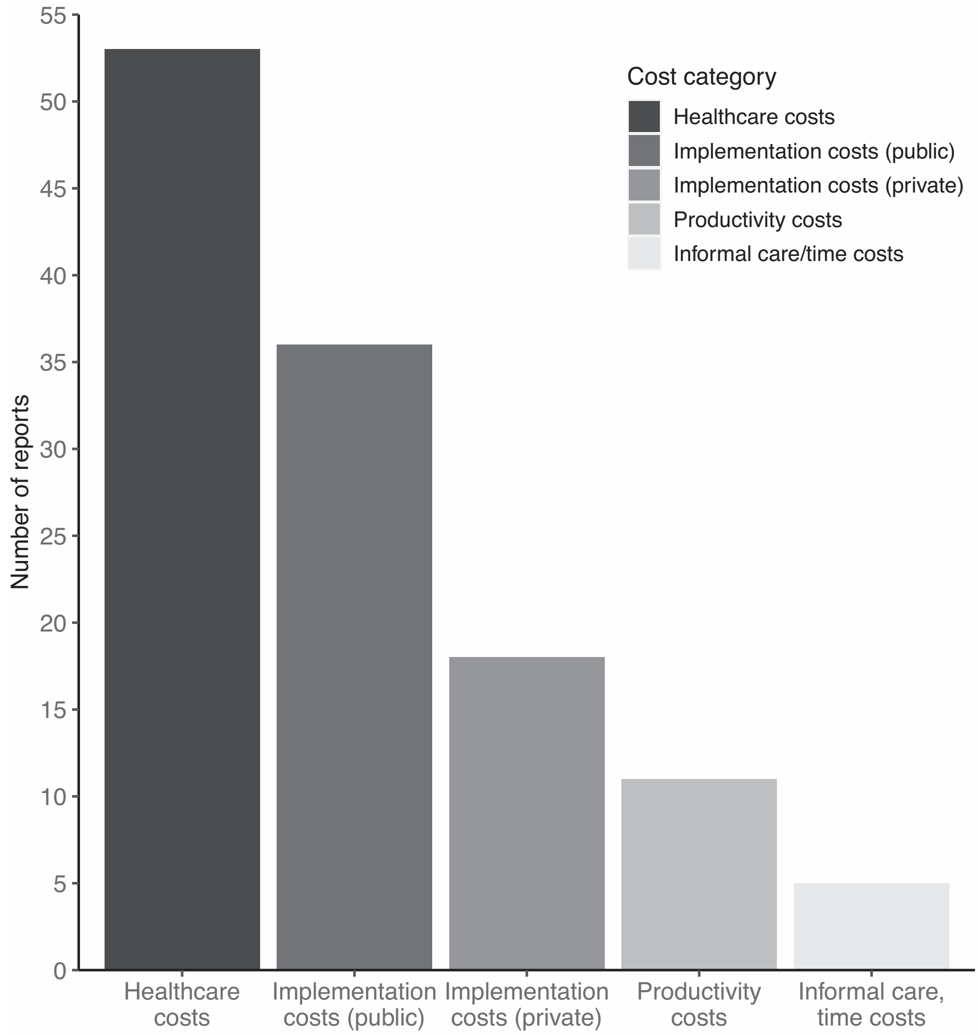

FIGURE 5 Bar plot of number of studies assessing different cost categories. Reported and included cost categories based on 56 modeling studies. Categories are aggregated from subcategories in Table 1.

subsidy) that targeted more diverse food groups (e.g., healthy and unhealthy foods).

Model risk factors and health outcomes

The range of implementations across all model types and modeling studies covered the main diet-related cardiometabolic outcomes, cancer, osteoarthritis, cirrhosis of the liver, and dental caries. Sorted by frequency, the health outcomes modeled most often were CVD [e.g., angina, heart failure, coronary heart disease (CHD)] ($n = 46$ studies), stroke ($n = 37$), type 2 diabetes ($n = 24$), different cancers (e.g., endometrial cancer, colon cancer) ($n = 17$), osteoarthritis ($n = 10$), obesity ($n = 4$), dental caries ($n = 3$), and cirrhosis of the liver ($n = 1$) (Supplemental Table 1).

The mean number of health outcomes included in a given modeling study varied widely depending on model type: Markov multistate life table models incorporated, on average, 4.8 health outcomes; microsimulations, 2.9; standard Markov models, 2.3; and CRA models, 1.6. Two studies modeled only a single health outcome, although evaluating policies with extensive health effects, thus potentially underestimating cost-effectiveness (51, 52).

Few studies (11/56) modeled only the direct relation between nutritional targets and health outcomes (e.g., TFA intake → CHD). Beyond direct pathways, 7 intermediate risk factors (e.g., salt/sodium intake → blood pressure → CHD) were included in modeling studies: BMI ($n = 30$ studies), blood pressure ($n = 26$), cholesterol (i.e., HDL, LDL, or total cholesterol) ($n = 14$), smoking behavior ($n = 12$), type 2 diabetes (risk factor for CVD) ($n = 11$), the Alternative Healthy Eating Index ($n = 1$), and triglycerides ($n = 1$).

Figure 3 shows how often nutritional target → risk factor → outcome pathways were explicitly considered in the studies included in this review. This means, for example, that, although 26 of 56 studies included blood pressure as a risk factor, blood pressure presents a small share of all pathways modeled because it is mainly relevant for salt/sodium and CVD or stroke. BMI, on the other hand, is not only often included as a risk factor in dietary policy evaluations but also serves as the main intermediate risk factor for many nutrition–health outcome pathways in these studies.

Model validation and uncertainty

Validation information was reported in less than half (19/56) of the modeling studies. The remainder only referred to other studies for methodological documentation without justifying the deduced validity of the respective model or did not report on this aspect. Although most studies included a paragraph briefly describing modeling methods, comprehensive supplementary material transparently presenting the model structure and underlying equations was often lacking (Supplemental Table 3).

Uncertainty in outcomes was assessed in all but 1 study (66). Most (36/56) studies addressed parameter uncertainty (second-order uncertainty) (13) using probabilistic sensitivity analysis with sampling from parameter distributions (i.e., Monte Carlo sampling). Deterministic sensitivity analysis with variation of parameters across predefined ranges was performed in 8 studies. All 11 microsimulation models assessed overall uncertainty of estimates by incorporating individual-level stochastic uncertainty (first-order uncertainty) and parameter uncertainty (second-order uncertainty) simultaneously (Supplemental Table 1).

Population health measures and equity

Reported population health measures were categorized into epidemiological metrics (i.e., incidence, prevalence, and mortality), health-adjusted or unadjusted life-years [i.e., QALYs, DALYs, health-adjusted life-years (HALYs), life-years (LYs), and life-years gained (LYG)], and life expectancy and other measures (i.e., person-years, total cases, health care utilization). Incidence and mortality were the most commonly reported metrics (59 and 44 reports, respectively) (Figure 4A and Table 1). QALYs were reported in 21 of 56 studies, and 19 of 56 studies reported DALYs. Six and 12 of 56 studies reported HALYs and LYs or LYG, respectively. A single study estimated a change in life expectancy (Figure 4B and Table 1).

Only a few studies (13/56) conducted a quantitative equity analysis and assessed the potentially heterogeneous impact of dietary policies on health and economic outcomes according to age (32, 57, 58, 60, 61, 70, 78), sex (32, 57, 58, 61, 70, 78), ethnicity (32, 57, 58, 61, 78), area-based deprivation (26, 46, 47, 60), or income (55, 68–70). One study qualitatively examined the equity aspects of an SSB tax (49) (Table 1).

Beyond these, some studies (22/56) reported health or cost outcomes stratified by sociodemographic variables without specifically aiming to analyze the impact on health inequalities, from which equity considerations may nonetheless be derived (Table 1).

Cost components and evaluation perspective

Almost all studies (52/56) included formal health sector costs in their economic analysis, although not all these studies included disease cost offsets (i.e., potential future treatment cost savings) (Figure 5 and Table 1). Informal health sector costs (i.e., informal care and time costs) were only included in 3 studies.

Regarding costs outside the health sector, implementation costs (e.g., legislation) in the public sector were considered by 35 studies, whereas 18 studies included implementation costs in the private sector (e.g., product reformulation, package design).

Only 11 studies included costs resulting from lost productivity (e.g., unemployment, absenteeism, presenteeism) (Table 1), of which the majority (9/11) used a partial or full human capital [lost productivity is calculated based on all potential earnings lost due to illness (employee perspective)] as opposed to a friction costing approach [lost productivity is calculated based on potential earnings lost during a friction period until replacement by another employee (employer perspective)].

After redefining costing perspectives, we found that 17 studies used an extended health sector perspective, 12 studies a societal perspective, 10 studies used a limited societal perspective, 9 studies used a health sector perspective, 4 studies applied the generalized cost-effectiveness analysis (GCEA) framework from the WHO (85), and 2 studies evaluated costs from a government perspective. For 10 studies the choice of perspective was not reported and derived by the author team based on the included cost categories (health sector: $n = 3$; limited societal: $n = 5$; societal: $n = 1$; UK National Health Service: $n = 1$). A comparison between multiple costing perspectives was only performed by 6 studies (Table 1).

Population health measures in relation to cost

Of 56 studies, 32 reported an ICER, and 3 additionally reported the net monetary benefit of policies (Table 1). The net monetary benefit combines the ICER with the willingness of a society to pay for a certain gain in health utility, thus placing a monetary value on health, and enables direct national comparisons across diseases and policies. One caveat is that some authors might have chosen not to report ICERs because the evaluated policy was cost-saving, making interpretation infeasible (79).

As we did not adjust reported cost values for purchasing power parity, we were not able to directly compare cost-effectiveness, cost-utility, or cost-benefit between policies and countries. Instead, we indicated whether studies considered the policy under evaluation to be cost-saving.

Independent of the perspective chosen, a majority of applications (103/136) considered the dietary policy under evaluation to be cost-saving (Table 1). For 3 model applications, a comparison of costing perspectives led to the policy being cost-saving from the more extensive perspective (45, 56).

Limitations reported by authors

We used limitations reported by the authors of the included modeling studies to synthesize considerations for

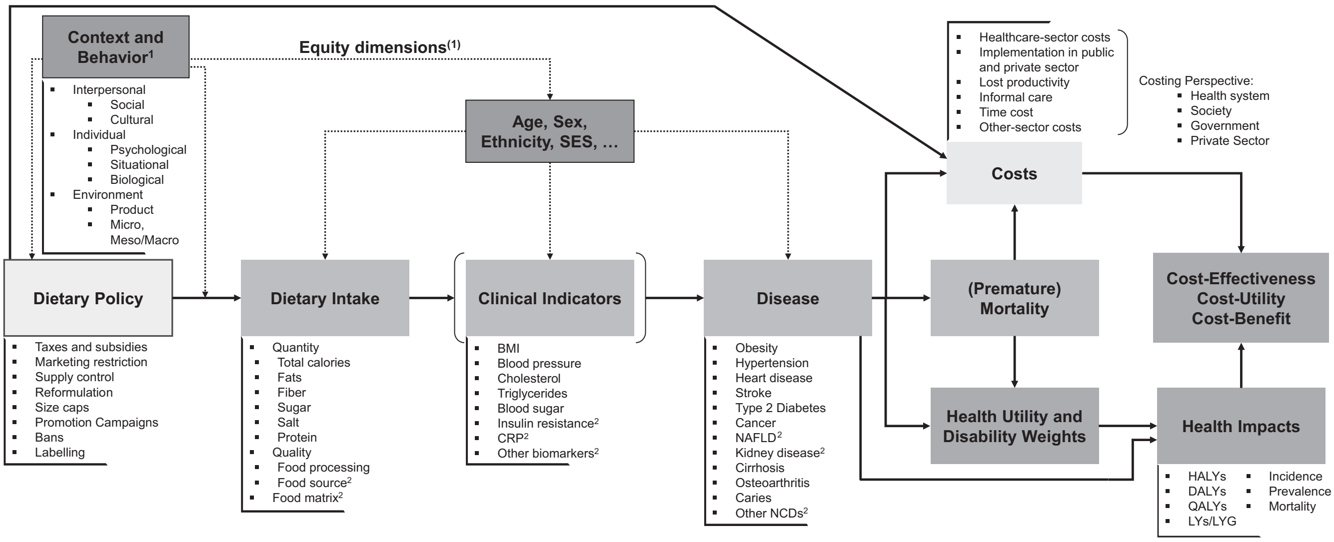

FIGURE 6 Logic model of the prototypical operationalization of economic dietary policy evaluations including context factors and equity dimensions. All elements deduced from the included modeling studies unless indicated otherwise. [1]Contextual and behavioral factors and some potential equity dimensions based on Symmank et al. (86). [2]Based on Mozaffarian et al. (87). CRP, C-reactive protein; DALY, disability-adjusted life-year; HALY, health-adjusted life-year; LY, life-year; LYG, life-year gained; NAFLD, nonalcoholic fatty liver disease; NCD, noncommunicable disease; QALY, quality-adjusted life-year; SES, socioeconomic status.

dietary policy evaluations that use public health economic simulation models. The following 6 major themes were identified (see Table 1 for details per study): *1*) validity and uncertainty of effect estimates (e.g., relative risk of disease per 5 g nuts and seeds intake/d) from observational studies, which might lead to overestimation of health gains due to false positives; *2*) nonconstant intervention effectiveness and limited long-term real-world impact through unpredictable behavioral changes and secular trends; *3*) information biases in underlying epidemiological population data, which may distort conclusions (e.g., underreporting of food intake); *4*) disregard of lost productivity and potential tax revenue re-investment (i.e., earmarking), which leads to underestimation of health and economic impacts; *5*) disregard of equity dimensions of policies; and *6*) lacking assessment of structural model uncertainty.

Discussion

Main findings

In this systematic scoping review, we mapped economic evaluations of population-based dietary policies using public health economic simulation models. We identified a large body of literature with 56 modeling studies consisting of 136 applications covering 21 different countries or regions. The policies under evaluation addressed a wide variety of population-based approaches to diet-related NCD prevention with different levels of granularity. Various types of public health economic simulation models such as Markov cohort models and individual-level microsimulation were applied with distinct patterns emerging (Figure 2). Overall, the most important NCDs and risk factors with dietary relevance were covered, albeit only 1 study included a summary measure of diet quality (i.e., the Alternative Healthy Eating Index) as an intermediate risk factor (Figure 3). Uncertainty was assessed in most studies, but only a few documented internal or external validation procedures. Our analysis of authors' limitations identified substantial challenges, particularly regarding validity of effect estimates and long-term dietary policy effects.

A logic model of economic evaluations in dietary policy

Based on our mapping process, we developed a logic model that describes how dietary policy evaluation is operationalized in public health economic simulation models (**Figure 6**). It visualizes the implicitly causal structure that studies assume to model dietary policy impacts.

We enhanced the logic model with aspects discussed in the literature on dietary behavior and policy evaluation that were not covered by the included studies. For this, we used the results of a systematic interdisciplinary mapping on the determinants of food behavior from the Knowledge Hub on the DEterminants of DIet and Physical Activity and a recent review of dietary policy as guidance (86, 87). We aimed to highlight factors that go beyond what was modeled in the reviewed studies.

The logic model provides a visual reference throughout the next sections to help discuss our results compared with a prototypical model. It thereby provides a connection to broader implications of dietary policy evaluation.

Population-based dietary policies and nutritional targets

In this review, 4 major policy types were covered with different mechanisms to improve population diets and economic aspects of implementation:

- First, population education policies such as health-promotion campaigns that aim to educate individuals to change their behavior but can be very costly to maintain on a larger scale (88).
- Second, policies modifying point-of-purchase information such as nutrient-specific labels, which seek to passively increase public awareness of healthy dietary choices and rely more on structural elements of consumer choice. The implementation of voluntary or mandatory labels can be politically challenging, with the majority of implementation costs typically borne by the private sector (89).
- Third, reformulation policies, which set quality standards for food processing and limit additives such as sugar, salt, and TFAs. Such policies can be more effective than consumer information with minimal public and private sector costs once they are established (88).
- Finally, fiscal policies including taxes, subsidies, and other financial incentives, which rely on individual sensitivity to price changes and generate revenue that can be earmarked for other health policies (90).

Although a large variation in food groups and nutrients relevant to NCD prevention was evaluated in this review, 71 of 136 applications evaluated reformulation or fiscal policies in relation to salt/sodium or SSBs (Table 1 and Figure 2). While these are responsible for a large share of the burden of NCDs, the corresponding etiologic pathways are well established, and many countries consider or have already implemented such policies, they represent only part of the broader picture on population-based dietary policy (91) (Figure 6).

From a nutritional point of view, this represents a degree of undercomplexity in the structure of public health economic simulation models considering newer findings on the relevance of the overall nutrient composition of foods, interaction of those nutrients, and dietary quality beyond macronutrients (87) (Figure 6). Only 1 study in this review (16) uses a summary measure of diet quality (i.e., the Alternative Healthy Eating Index) as a risk factor, and 2 studies evaluate policies targeting a distinct set of healthy and unhealthy foods as defined by recent evidence (48, 56) (Table 1).

Similarly, only 14 policy applications focus on foods that were processed in some form (Table 1). Although the evidence of the direct effect of food processing on human health is not fully understood, ultra-processed foods typically have high energy density and contain high amounts of unhealthy fats, sugars, and sodium (92–94). Policies addressing food processing and processed-food consumption may play an important role in NCD prevention (95) and should be supported by economic evaluations to assess their compatibility with other strategies (Figure 6). A caveat is that studies evaluating dietary policy in children (which were excluded in this review) are likely to focus on more processed foods (96).

From a policy perspective, there is a scarcity of evaluations of multicomponent policies combining structural and agentic elements, the cost-effectiveness of which is of great relevance for effective large-scale NCD prevention (10, 88, 97). Yet, only 11 of 136 applications evaluated such combinations of policies. A comprehensive strategy could, for example, use different taxes, subsidies, and accompanying information campaigns together with advertisement restrictions (87, 88).

Only a few studies included in this review evaluated dietary policies in low- and middle-income countries [as defined by the Development Assistance Committee of the Organization for Economic Co-operation and Development (98)]. Although likely the result of our search strategy restriction to articles published in English, this might be also related to the high data requirements and resources needed to conduct economic evaluations of dietary policies using simulation modeling (14). This is important as obesity rates and the double burden of malnutrition are rising across the globe, increasing the need for evidence of cost-effective preventive policy options in all settings (99).

Key economic aspects for the evaluation of population-based dietary policies

Adherence to guidelines for health economic evaluation regarding the definition of costing perspectives and inclusion of cost categories was inconsistent across the reviewed studies. Because costing perspective is a key information for decision makers, consequent adherence to research and reporting standards including a discussion of deviations from them is important (82).

In the economic evaluation of population-based policies for the prevention of NCDs, costs beyond the health care sector (i.e., beyond future treatment savings) make up a substantial share of total costs and should be considered (100, 101). Yet, only a few studies include consequences for labor market outcomes or workplace productivity (e.g., early retirement, absenteeism, presenteeism).

Studies that compare different costing perspectives [e.g., Kim et al. (45)] show that the adoption of a societal perspective can substantially increase projected net savings from dietary policies (Table 1). One caveat to this is that lost productivity can be calculated in 2 ways, human capital versus friction cost, yielding different results, the respective superiority of which is a subject of ongoing debate in health economics.

The choice of a health sector perspective itself—and thus the exclusion of costs from lost productivity—does not constitute a limitation from a health economics viewpoint.

But, because of the population-based character and corresponding large-scale impact of many dietary policies, a societal perspective seems most appropriate, and comparison of multiple perspectives is recommended (25). Because inertia in knowledge exchange between policy sectors often leads to an underestimation of the economic benefits of health-promotion efforts, quantifying costs beyond the health care sector is crucial for dietary policy implementation (102) (Figure 6).

The 2 most important cost categories accruing during the implementation of population-based dietary policies are private and public sector policy costs. These are distinct from intervention costs in community or clinical settings.

Private sector costs are mainly relevant for policies where businesses must adjust production procedures, recipes, or package design, such as reformulation and packaging regulations (including labeling). Valid estimation of private sector implementation costs is complicated by conflicts of interest and nondisclosure on the part of the food industry. Although some studies use government tools to approximate private sector costs (15, 61), most evaluations do not consider them or use very rough calculations linked to public sector implementation costs (e.g., setting them equal).

Depending on the type of policy, public sector implementation costs are the only cost driver of population-based policy and thus should be considered carefully. Yet, implementation costs of, for example, a tax, although implicitly appraisable by assuming hypothetical legislation costs, can only be calculated very roughly.

Public health economic simulation model types and dietary policy evaluation

Types of public health economic simulation models in this review cover a wide range of cohort- and individual-level approaches from generic single-use Markov models [e.g., Dalziel and Segal (39)] to established and continuously developed microsimulation models [e.g., Huang et al. (15)]. Although there is no one-size-fits-all solution, relatively simple approaches, such as CRAs, may give similar results, compared with, for example, a complex microsimulation, for a given policy evaluation depending on the granularity of the policy itself (12). Comparative modeling studies can support the assessment of this structural uncertainty and strengthen the trust for model-based evidence (see "Transparency and open science in dietary policy evaluation" below). However, for the modeling of very specific dietary policies, which, for example, target subfood groups or rely on mechanisms that require time- and event-dependent interaction (e.g., substitution), individual-level models are generally more suitable. Additionally, the availability of data and requirements for the timely, transparent communication of results with stakeholders all influence the choice of model type beyond purely methodological considerations (103).

An important observation is that, in recent years, there has been a tendency toward increased model complexity with the detailed simulation of individual risk factor and disease trajectories accounting for diverse socioeconomic features. The primary reason for this may be increasing availability of computational resources and granular input data required to conduct such sophisticated simulations.

We did not identify studies using model types that enable individual environment interaction (e.g., agent-based simulation) or resource constraints (e.g., system dynamics models). For some dietary policies, agent-based models might be preferred, as they allow the integration of a more valid representation of consumer environment behavior, thus producing important insights into policy impacts (12). Although increasingly sophisticated simulation models require even more granular input data and very specific, but nonetheless valid, parameters, these methods could be better suited for the evaluation of some policy types.

Validity considerations for dietary policy evaluation

Apart from the choice of model type, key considerations for dietary policy modeling are, first, the quality of dietary data, and second, the reliance on effect estimates from observational studies.

Individual dietary data on the consumption of foods and intake of nutrients within a predefined time period are one of the most important inputs for the reviewed models. However, reliable and valid collection of these data, which are typically collected using food-frequency questionnaires, 24-h dietary recalls, food diaries, or food-purchasing information is complicated and susceptible to information biases such as social desirability bias (104). In the case of purchasing data, food waste may need to be considered (105, 106). Although considerable efforts are made to mitigate these biases and intake data can be adjusted for (e.g., underreporting), this remains an important limitation (107).

Further, nonrandomized studies can produce biased results, especially in the field of nutritional epidemiology (108) and thus have to be interpreted with caution. Although some pathways, as discussed above, can be seen as causal, a better understanding of the health effects of dietary patterns and overall diet quality is needed (87). On the other hand, randomized controlled trials of dietary interventions have particular challenges, sometimes resulting in questionable external validity for real-world policy (109).

A central limitation with all modeling studies in this review remains (long-term) external validity, which is usually performed by comparing model projections with observed data that were not part of the model fitting process (110). As most of the dietary policies evaluated are not actually implemented, outcomes are projected far into the future, and factors beyond dietary policy influence disease incidence, statements about substantial health gains need to be interpreted with caution. Therefore, future studies need to quantify the health and economic effects that are attributable to implemented dietary policies once sufficient time has passed for the corresponding health outcomes to potentially be prevented (111).

Translation from experimental evidence of potential policy mechanisms to real-world policy impacts is not always easy to establish. For many types of dietary policies, these mechanisms, such as consumer reactions to changes in price, are well researched (112). Yet, policymakers may draw only preliminary conclusions from these studies which, in the absence of alternatives, are also often the foundation for effect estimates used in simulation studies. It is therefore crucial for stakeholders and researchers to evaluate every step of the logic pathway (Figure 6) from policy to health and economic outcomes in a real-world setting.

Early international evidence suggests that some policies indeed work as intended (e.g., taxes on SSBs increase prices and decrease SSB consumption) but a translation to measurable real-world health outcomes is yet to be observed (113–115). Complementary ex post evaluations using econometric causal inference methods such as difference-in-difference or synthetic control approaches on observational data can help improve the evidence base in this regard (116).

One issue particularly compromising long-term validity may be that authors sometimes assume stable long-term effects over unrealistic time horizons (e.g., lifetime of the population) without including rebound effects. For some policies, such as health-promotion campaigns, which might be implemented iteratively, diminishing re-intervention effects need to be considered as well.

Transparency and open science in dietary policy evaluation

To mitigate some of the above-mentioned issues, transparency and adherence to quality standards in the conduct and reporting of studies using public health economic simulation modeling are important. Published models need to be explicit about all their assumptions and limitations pertaining to policy effects, input data, and validation. The provision of comprehensive supplementary material and the public sharing of code on online repositories such as GitHub or the Open Science Framework are key components of this transparency.

Although some frameworks for the quality assessment of simulation models and economic evaluations using such models exist, these are primarily aimed at application in health technology assessment (25, 117).

For this reason, we extended and adapted the established CHEERS checklist for the quality appraisal of economic evaluations as described in the Methods section. Even though this revised checklist is not validated by experts, it can serve as a preliminary baseline to judge and compare the overall quality of economic evaluations of dietary policies using public health economic simulation models. Through the inclusion of key considerations for simulation modeling and dietary policy evaluation such as validation, calibration, and transparency and making explicit the dietary target and policy under consideration, it enables the identification of high-quality studies in this review.

Nonetheless, work toward a consistent set of guidelines specifically for public health economic simulation modeling of NCDs with clear recommendations for relevant behavioral and proximal risk factors, diseases, and health outcomes, including complementing guidelines for economic evaluations, should be considered. For this purpose, the Mt. Hood Diabetes Challenge Network could serve as an example (118). This might imply a considerable effort among the research community but will support authors, peer-reviewers, and decision makers to benchmark the quality of modeling studies, increase comparability, and ultimately strengthen trust in model-based projections by policymakers.

In contrast to other areas, such as infectious diseases or cancer progression modeling, in dietary policy evaluation no comparative modeling studies have been published so far. Such studies compare 2 or more model types (e.g., microsimulation vs. Markov cohort models) or implementations of the same type (e.g., 2 independently developed Markov cohort models with different features) using the same input data to assess differences in outcome projections (119). The influence of effect estimates sourced from various meta-analyses on outcomes could also be compared.

These techniques may give important insights into structural model uncertainty, such as the choice of included risk factors, and foster a more thorough discussion of model assumptions and outcomes. As all "models are wrong, but some are useful" (120), comparing different independently developed models, using different modeling techniques, can increase the credibility of the results in a similar way to meta-analyses (119).

Equity and context in dietary policy evaluation

From an economic perspective, population-based preventive policy can be a means to address an undesirable distribution of social welfare, including health (102).

Socioeconomic factors are important in the economic evaluation of population-based dietary policies because dietary, health, and economic disparities are correlated across population subgroups (Figure 6) (86). Yet, only a few studies recognize the heterogeneous effects of dietary policies on health outcomes across different equity dimensions, although this was identified by some authors as a limitation to their modeling (Table 1).

The mechanism of a policy can moderate differential health effects according to dimensions such as age, gender, race, and income (80). As an example, because low-income groups have a higher baseline consumption of taxed unhealthy products and a higher price elasticity of demand, taxation strategies can be regressive—having a larger impact on those with low incomes—depending on their design (112).

Acknowledging this can not only reduce health disparities through dietary policy by, for example, earmarking part of a tax revenue generated for nutrition programs supporting communities with low dietary literacy, but also lead to more cost-effective dietary policy by reducing the health burden in highly-affected groups (121).

Future studies should use the flexibility of individual-level approaches more often to explicitly model effects across heterogeneous subpopulations and assess to what degree dietary policies increase or decrease health inequalities. This can help with finding the optimal design and combination of policies by comparing health, equity, and cost implications.

Limitations

Our review has some important limitations. First, we post hoc excluded subsets of studies in accordance with our protocol (Figure 1). We also excluded studies evaluating policies addressing children and adolescents, although they are an important target of NCD prevention efforts including dietary policies such as healthy meals and vending machine bans in schools. In line with this decision, we also excluded economic evaluations of dietary policies in specific settings such as primarily addressing individuals in high-risk groups through dietary counseling in primary care and studies only including other subgroups such as indigenous people. Second, the number of epidemiological modeling studies evaluating only the effectiveness of policies is much higher than the number of economic modeling studies, most of which essentially build on the same model types but also include aspects of health-related quality of life and costs. We might therefore have missed some potentially viable model implementations, which could be supplemented with an economic module. Third, we restricted our search to studies published in English, thus potentially overlooking eligible modeling studies published in other languages.

Conclusions

In conclusion, different types of public health economic simulation models exist and are widely applied for evaluations of population-based dietary policies. The reviewed studies address most policy types, nutrients/food groups, risk factors, and health outcomes relevant for diet-related NCD prevention. A substantial number of applications evaluate labeling, reformulation, and taxation policies that target salt/sodium and sugar (including SSBs and snacks/sweets). Few studies estimate lost productivity as part of their economic evaluation, which is key information for stakeholders outside the health sector. In recent years, advanced microsimulations have been used to evaluate more complex policies and nutritional targets, yet only partially incorporating dietary complexity beyond a single-nutrient/food-group focus. These models are also better suited to incorporate population heterogeneity and analyze correlated social, health, economic, and equity impacts, which only a minority of studies examine. The choice of modeling method is dependent on policy type, and extensive data requirements for individual-level models may limit application in some contexts where good dietary and epidemiological data are not available. Lack of knowledge about long-term intervention effects, potential unintended policy consequences on dietary behavior, and secular disease trends represent key limitations of current economic evaluations of population-based dietary policies. There is still considerable uncertainty about real-world health economic policy impacts, and the external validity of public health economic simulation models needs to be carefully assessed based on the available data and future studies. Transparency in model application and dissemination based on open-science guidelines can increase the trust of stakeholders in the results of modeling exercises and ultimately strengthen NCD prevention efforts.

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A.2. Estimating the impact of nutrition and physical activity policies with quasi-experi-mental methods and simulation modelling: an integrative review of methods, challenges and synergies

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Summary of methods and results:[‡]

The objective of this study was to review the strengths, limitations, methodological assumptions and synergies of simulation modeling and quasi-experimental approaches to evaluate nutrition and physical acticity policies. We particularly focused on providing guidance for stakeholders and discussing the application of both methods within a comprehensive approach to policy evaluation.

We conducted an integrative review applying purposive literature sampling methods to give a targeted and selective overview of the research on the application of simulation modeling and quasi-experimental approaches to evaluate nutrition and physical policies. We therefore did not strive to provide a full systematic overview but to focus on seminal original articles and systematic reviews identified during our work within PEN. We supplemented these studies with literature identified using forwards and backwards citation searches and relevant data from two expert workshops on policy evaluation conducted in PEN[†]. For the purpose of our literature selection, quasi-experimental methods were defined as using observational data to estimate treatment effects applying the Neyman–Rubin counterfactual framework. Simulation modeling was define as methods and techniques to create abstractions of real-world phenomena with mathematical equations combining various sources of information.

Based on the selected literature we explained the theoretical foundation of causal inference in natural experiments using quasi-experimental study designs such as DiD, RDD, and IV analyses which aim to separate selection bias from the true policy effect. We further summarized the key assumptions for these study designs, such as the parallel trends assumptions for DiD studies, and discussed analytical strategies and the data needs to test them. Important areas of development for future applications of quasi-experimental methods to evaluate public health policies that we identified included

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[‡]We explicitly do not provide references in this short summary and refer to the respective publication.

[†]The materials of the workshops are available at osf.io/fnmgk and osf.io/azf3n.

the assessment of heterogeneity in policy treatment effects and the exploitation of novel data sources for nutritional and physical activity behavior such as large-scale household scanner and accelerometer data. With regards to simulation modeling we summarized their premise of using epidemiological principles to project NCD health trajectories over time. We here particularly emphasized their usefulness in projecting policy implications over a longer time horizon and for NCD outcomes which are further away from concrete policy effect in the causal pathway from nutrition to disease. Using identified seminal studies in the field we discussed types of simulation models, their assumptions, such as the Markovian *no-memory* assumption in the case of Markov cohort models, and their respective data and computational requirements. Future challenges of the application of simulation models to evaluate policies in nutrition and physical activity included the validity of etiologic effect estimates which are often non-causal, model validiation, and the appreciation of heterogeneous policy effects.

Acknowledging that quasi-experimental methods and simulation modeling are important tools in policy evaluation we developed a conceptual framework to integrate the strengths, limitations, and synergies of both approaches. Quasi-experimental methods are able to provide design-based causal estimates but their assumptions do not hold over long time horizons. Simulation models on the other hand need these causal estimates and are able to exploit epidemiological principles to project chronic disease outcomes over several years. We therefore argued that both methods should be applied together to provide robust evidence on public health policies for policymakers.

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Estimating the impact of nutrition and physical activity policies with quasi-experimental methods and simulation modelling: an integrative review of methods, challenges and synergies

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Background: The promotion of healthy lifestyles has high priority on the global public health agenda. Evidence on the real-world (cost-)effectiveness of policies addressing nutrition and physical activity is needed. To estimate short-term policy impacts, quasi-experimental methods using observational data are useful, while simulation models can estimate long-term impacts. We review the methods, challenges and potential synergies of both approaches for the evaluation of nutrition and physical activity policies. **Methods:** We performed an integrative review applying purposive literature sampling techniques to synthesize original articles, systematic reviews and lessons learned from public international workshops conducted within the European Union Policy Evaluation Network. **Results:** We highlight data requirements for policy evaluations, discuss the distinct assumptions of instrumental variable, difference-in-difference, and regression discontinuity designs and describe the necessary robustness and falsification analyses to test them. Further, we summarize the specific assumptions of comparative risk assessment and Markov state-transition simulation models, including their extension to microsimulation. We describe the advantages and limitations of these modelling approaches and discuss future directions, such as the adequate consideration of heterogeneous policy responses. Finally, we highlight how quasi-experimental and simulation modelling methods can be integrated into an evidence cycle for policy evaluation. **Conclusions:** Assumptions of quasi-experimental and simulation modelling methods in policy evaluations should be credible, rigorously tested and transparently communicated. Both approaches can be applied synergistically within a coherent framework to compare policy implementation scenarios and improve the estimation of nutrition and physical activity policy impacts, including their distribution across population sub-groups.

Introduction

The promotion of healthy lifestyles has gained high priority on the public policy agenda over the last two decades. There is a growing demand for the credible estimation of policy impacts and evidence on the real-world effectiveness and cost-effectiveness of different population-based strategies addressing nutrition and physical activity.[1,2] Yet, relative to clinical interventions, public policies are hard to randomize and it is thus a challenge to control for confounding factors and behavioural biases.[3]

Hence, quasi-experimental methods (QEM) using observational data for policy evaluation have become increasingly popular (table 1).[4] Despite the availability of this quantitative toolbox, which is successfully applied in the social sciences, especially labour economics (see the 2021 Nobel prize in Economics, Royal Swedish Academy of Sciences, 2021), its application to identify causal effects of nutrition and physical activity policies on health outcomes is complex and potentially not fully exploited.[5]

Because the policy-behaviour-health causal link is probabilistic, delayed over time and the required data, particularly in the case of many confounding factors, may not be available, QEM cannot provide evidence on the long-term impact on health outcomes.[6] Consequently, mathematical disease simulation models (SMs) projecting the long-term health and economic consequences are increasingly considered by scholars and policy makers (table 1).[4,7,8]

This article reviews QEM and SM approaches for the evaluation of nutrition and physical activity policies, their strengths and limitations, as well as their underlying general methodological assumptions. We show the complementarities of QEM and SM and discuss how their different characteristics could be exploited in a synergetic fashion to develop a more comprehensive concept of policy evaluation. We aim to provide guidance for applied researchers, policymakers and other stakeholders focussing on QEM and SM as two rapidly evolving methodological frameworks.

Methods

We conducted an integrative review of assumptions, data requirements, strengths, limitations and synergies in the application of QEM and SM to evaluate population-based nutrition and physical activity policies. An integrative review approach enables the synthesis of diverse methods and types of information to provide a more comprehensive understanding of a research area. Integrative reviews are targeted and selective in nature and apply purposive literature

Table 1 Google Scholar search of evaluation methods for nutrition and physical policies over three decades

Keywords	*N*, 1991–2000	%	*N*, 2001–10	%	*N*, 2011–20	%	Ratio 2011–20 vs. 1991–2000
Nutrition policy (total)	*5560*[a]	*100*	*13 300*	*100*	*17 200*	*100*	*3.1*
Nutrition policy & randomized controlled trial	124	*2.2*	840	*6.3*	2820	*16.4*	*22.7*
Nutrition policy & quasi-experimental	50	*0.9*	253	*1.9*	812	*4.7*	*16.2*
Nutrition policy & difference-in-difference	1	*0.0*	41	*0.3*	186	*1.1*	*186.0*
Nutrition policy & simulation	299	*5.4*	553	*4.2*	1190	*6.9*	*4.0*
Nutrition policy & microsimulation	4	*0.1*	30	*0.2*	121	*0.7*	*30.3*
Physical activity policy (total)	*37*	*100*	*706*	*100.0*	*2640*	*100.0*	*71.4*
Physical activity policy & randomized controlled trial	4	*10.8*	74	*10.5*	565	*21.4*	*141.3*
Physical activity policy & quasi-experimental	2	*5.4*	75	*10.6*	287	*10.9*	*143.5*
Physical activity policy & difference-in-difference	0	*0.0*	0	*0.0*	25	*0.9*	*NA*
Physical activity policy & simulation	3	*8.1*	32	*4.5*	106	*4.0*	*35.3*
Physical activity policy & microsimulation	0	*0.0*	0	*0.0*	8	*0.3*	*NA*

[a]: Italic values indicate total amount of identified articles with the respective keyword.

sampling techniques.[9,10] Thus, the aim, in contrast to a systematic review, is not to provide an exhaustive, systematic overview of a specific topic.

The starting point for our purposive searching comprised key original articles and systematic reviews identified by the author team within the European Union Policy Evaluation Network (PEN) project, which described the methodological assumptions and application of QEM and SM to evaluate population-based nutrition and physical activity policies.[8,11,12] From these, we conducted purposive snowball searches to identify further key references based on subject matter expertise of the author team. The result of this approach does not represent a comprehensive list of all relevant original articles and systematic reviews, but a diverse selection of studies useful for exploring the strengths, limitations and applications of QEM and SM.

We defined QEM as all methods using observational data to estimate treatment effects (TEs) in the Neyman–Rubin counterfactual framework and SM as methods and techniques, which use mathematics to create abstractions of real-world phenomena with computer software from various sources of information.[13,14]

For each identified original article and systematic review, we extracted data on the general method (i.e. QM or SM), the specific type of method used or reviewed [e.g. difference-in-difference (DiD) analysis, Markov cohort SM], the underlying method-specific assumptions and limitations discussed and contextual information.

Additionally, we drew relevant data from the presentations of renowned scholars in QEM and SM at two public international workshops conducted within the European Union Policy Evaluation Network (PEN) project in Munich and Rimini in 2021 (materials available at: https://osf.io/fnmgk/ and https://osf.io/azf3n/).[11]

From these data sources, we synthesized key contemporary considerations in the application of QEM and SM. Specifically, we integrate an overview of QEM and SM methodology and summarize strengths and limitations, as well as the most important assumptions, future directions and synergies of both approaches in the evaluation of nutrition and physical activity policies.

Results

Quasi-experimental methods

Estimating the impact of a policy requires isolating the cause-effect path from a variety of confounding factors, i.e. causal inference.[12] Outside the experimental setting, policy evaluation relies on observational data from so-called 'natural experiments' (NEs). Due to the lack of randomization, selection bias needs to be addressed to estimate the true policy effect.

We consider NE to be any setting where the statistical selection process, which determines whether subjects are exposed to the policy or not, is neither controlled, nor known by the evaluator and depends on uncontrollable external factors.[15] The presence of uncontrollable external factors guarantees that the policy exposure is probabilistic. Although these probabilities are unknown and unknowable, this condition opens the way to statistical techniques for causal inference.[15]

This definition includes evaluations of nutrition and physical activity policies where exposure explicitly depends on subject characteristics, or because of indirect influences on participation.[15] These factors might be measurable and available (e.g. residence, age and income), but also difficult to measure or not available (e.g. biological markers and psychological traits).

With NEs, exposure to the policy cannot be assumed to be independent from the outcome, as the external factors influencing the probability to be treated may also influence the outcomes. This means that the post-policy difference in the outcomes is a combination of policy impact and pre-existing selection bias.[12] QEM control for this selection bias by design, so that after conditioning on the factors driving the assignment mechanism, the probability of being treated is independent from the potential outcomes, as in randomized controlled experiments (RCEs).

Impact estimation is relatively straightforward if all these conditioning variables are observed, an assumption, which is called selection on observables or unconfoundedness.[16] However, this is hardly ever fulfilled. Beyond observables, data on relevant variables may be missing, or not accurately measured (e.g. psychological traits). These variables are called unobservables, and unbiased estimation of the policy impact implies the ability to control for both observables and unobservables.

Testing assumptions and considering heterogeneous response

The fundamental QEM, instrumental variable models (IV), DiD and regression discontinuity designs (RDDs) control for both observables and unobservables, under certain assumptions.[17] An extensive description of the methods is beyond the scope of this review and is provided elsewhere.[12,17,18]

We do not consider propensity score matching methods, which depend on the strongest formulation of unconfoundedness, as they require all relevant variables to be observable and any unobservable to be either non-relevant, or highly correlated with an observed variable. Hence, selection bias could be simply also addressed by a regression equation with the treatment status and all relevant covariates as explanatory variables.

Although implementing QEM methods is relatively straightforward with the appropriate (longitudinal) data, the real challenge lies in demonstrating that their underlying assumptions hold. Table 2 shows these assumptions for IV, DiD and RDD. Yet, in most cases no conclusive test exists and rigorous evaluations must present robustness and falsification analyses and support the credibility of their quantitative findings.[12] Robustness analyses should

Table 2 Testing assumptions and dealing with unobservables in QEM

Method	Data requirements	Assumption allowing to deal with unobservables	Tests (examples)	Key references
Instrumental variables	Cross-sectional post-policy and at least one valid instrument	Relevance (of the instrument in determining the probability to be treated)	Testing probit model coefficient (Wald test significance not enough, *F*-statistic on the instrument coefficients should be large)	Cunningham (2021)[17]; Imbens & Rubin (2015)[12]; Davies et al. (2013)[19]
		Exclusion restriction: the instrument is exogenous	Lack of correlation between an excluded instrument and IV estimates of the residuals (non-conclusive and only feasible under overidentification)	
		Monotonicity: changes in instrument act in the same direction for all subjects	Not testable, and usually not important, but sensitivity analyses are possible	
Difference-in-difference	Repeated cross-sections: at least one cross-section before and one after the policy. Panel: at least one observation before and one after. Multiple observations before the policy needed to test the common trend assumption	Common (linear) trend vs. differential linear trend in the outcomes without the policy	Using data before-policy only, regress outcome on observables, a linear trend, and an interaction between the linear trend and the group variable (Wald test on the latter coefficient)	Cunningham (2021)[17]; Imbens & Rubin (2015)[12]; Callaway & Sant'Anna (2021)[20]
		Common (non-linear) vs. differential non-linear trends in the outcomes without the policy	Panel regression of outcomes on observables and fixed time effects, plus the interaction between the fixed time effects and the group variable, using before-policy data only. If there is a common trend, the interaction terms are all non-significant	
Regression discontinuity design (RDD)	Cross-sectional post-policy and an assignment-to-treatment variable related to the outcome. Data before the policy useful for sensitivity analysis.	Continuity assumption (no jump of the outcome at the cut-off without the policy—for fuzzy RDD also continuity of the probability of treatment)	Ideal check: run the same RDD on data before the policy and find no change at the cut-off. Alternative: RDD using the observables as the outcome, expecting non-significant results (non-conclusive)	Cunningham (2021)[17]; Imbens & Rubin (2015)[12]; Lee & Lemieux (2010)[21]
		Linearity assumption vs. non-linear functional forms	Not testable, but sensitivity checks are essential. Especially relevant for external validity. Ideal: test linear, non-linear (polynomial) and non-parametric specifications on data before the policy. Alternative: check robustness of the treatment effect estimate using different non-linear and non-parametric specifications, and different bandwidths.	

RDD, regression discontinuity design.

demonstrate that relaxing one or more assumptions or changing analytical choices does not lead to substantial differences in the estimated policy impacts. Falsification analyses refer to the application of the methods to outcomes, target groups or time periods not affected by the policy, and should return non-significant estimates.

Under the appropriate conditions, not only can QEM be as effective as RCEs in eliciting the causal effect of policies, but they are potentially even superior in terms of external validity since they are free from some potential experimental biases (e.g. Hawthorne effect, sampling errors and compliance).[22]

A short but rigorous review of the key features and testing strategies for the application of QEM to public health studies is provided in Bärnighausen et al. (2017).[23] These method-specific tests on assumptions are especially important from our perspective: (i) relevance and exogeneity in IV studies;[19] (ii) test for differential nonlinear trends in DiD studies, and their consideration (at least in robustness checks) if data allows;[20] and (iii) the continuity assumption in RDDs, and the sensitivity of estimates to different functional forms and bandwidth selections.[21]

When estimating real-world policy impacts, it is important to consider that the actual impact—or TE—of the policy may be heterogeneous across exposed subjects, and average estimates (ATE) may thus be unsatisfactory. If subjects are exposed to the policy, but do not comply with the intervention, ATE estimates become problematic, as non-compliers are likely to systematically differ from both compliers and control subjects (i.e. reasons for compliance are correlated with TE). Consequently, two different TEs can be estimated: (i) considering all those exposed regardless of their compliance, which returns the average intention-to-treat effect; and (ii) considering treated subjects only, while accounting for the additional selection bias, which returns the local average treatment effect (LATE). When non-compliance is an issue, the LATE can be obtained through an IV estimator.[16] Furthermore, TEs may be heterogeneous between subjects due to the nature of the intervention (e.g. personalized nutrition or physical activity programmes) since its effectiveness primarily depends on subject characteristics. Recently, there is a growing interest in methods (mostly based on machine learning) that capture this heterogeneity of policy impact across subpopulations, by letting the TE depend on sample covariates.[24]

Applications and future directions

There are many examples of QEM successfully applied to the evaluation of nutrition policies.[25] Applications to physical activity policies are less frequent but increased over the last few years (e.g. Xie et al., 2021 or Nakamura et al., 2021).[26–28] The available methods are evolving together with the rising availability of large and detailed datasets on food consumption and physical activity. Specifically, consumer panels for food purchases and the emergence of innovative technologies for data collection over time (e.g. accelerometers and smartphone apps to measure physical activity) are valuable resources for QEM relying on longitudinal data. For example, synthetic control methods are a powerful approach when pre-policy data cover multiple periods and multiple non-treated groups (e.g. regions or states),[29,30] while quantile DiD models and LASSO estimators may be of use for the estimation of heterogeneous treatment effects.[31,32]

Simulation modelling

In the context of public health, SMs are usually used to simulate population health trajectories and the impact of health-related policies on risk factor trends, disease epidemiology, health-related quality of life and subsequent socio-economic consequences in populations using epidemiological and economic principles, but can also be extended to include macroeconomic and environmental aspects.[7,33–36]

For health policies that address unhealthy diets and physical inactivity as risk factors for non-communicable diseases (NCDs), such as type 2 diabetes, cardiovascular disease and cancer, these methods are of particular merit.[34,37,38] Since these diseases are characterized by a chronic, progressing aetiology and their risk accumulates over time, effects of preventive policies are only measurable after many years, whereas the upfront political and policy implementation costs occur immediately.[39]

Beyond projecting epidemiologic health outcomes, SMs can estimate the long-term healthcare cost savings and non-health sector implications (e.g. lost productivity and environmental impact) of policies and are often applied within health-economic modelling to compare multiple policy scenarios, generating valuable information for priority setting.[4,40] Finally SMs can provide policy impact corridors by simultaneously incorporating uncertainties from multiple sources.[41,42]

Simulation modelling methods and main applications

Over the last decades, a variety of SMs in public health were applied in landmark projects, such as the Australian Assessing Cost-Effectiveness (ACE) in Prevention study, the US Childhood Obesity Intervention Cost-Effectiveness Study (CHOICES) project, the US Food Policy Review and Intervention Cost-Effectiveness (Food-PRICE) project (https://food-price.org/) and the Organization for Economic Co-operation and Development's (OECD) Chronic Disease Prevention (CPD) modelling initiative.[38,43,44]

Table 3 Advantages, challenges and limitations of simulation modelling methods

Simulation modelling method	Data requirements	Advantages	Challenges and limitations	Seminal examples
Comparative risk assessment (CRA)	Population size and sex-age distribution; aggregated, stratified socio-demographic and epidemiological information on risk factors and diseases; risk factor–disease relationships; policy and intervention effectiveness	Easy to implement and low run times Straightforward communication to stakeholders Efficient integration of multiple risk factors and diseases	No explicit time component Only aggregate information Assumption of homogenous population No interaction and time-dependencies possible	Briggs et al. (2017)[45]; Collins et al. (2014)[46]
Markov (cohort) state-transition model	Population size and sex-age distribution; aggregated, stratified socio-demographic and epidemiological information on risk factors and diseases (incl. prevalence, incidence, case fatality and mortality); extensive data on risk factor–disease relationships to calculate transition probabilities; policy and intervention effectiveness	Comparably easy to implement with low number of health states Explicit time component (discrete steps) Allows for recurrence and looping Straightforward communication to stakeholders using figures Efficient integration of multiple risk factors and diseases (in combination with proportional multi-state life tables)	Only aggregate information Assumption of homogenous population Markovian assumption—no information on health status in previous time steps (no memory) Interaction and time-dependencies only possible for full (sub-)cohort and with complex model structures Complexity increases exponentially with number of health states	Cobiac et al. (2017)[47]; Vos et al. (2010)[43]; Carter et al. (2009)[48]
Microsimulation	Individual-level (repeated) cross-sectional or cohort data on socio-demographics and health behaviours from population health surveys; aggregated, stratified epidemiological information on diseases (incl. prevalence, incidence, case fatality and mortality); extensive stratified data on risk factor–disease relationships; policy and intervention effectiveness	Individuals instead of cohorts Explicit time component (discrete steps) High flexibility in model structure Allows for individual heterogeneity, complex interactions and time-dependencies Flexible estimation of various outcomes Can be used within CRA or Markov model framework	Can very quickly get very complex Communication with stakeholders can be difficult due to complexity Very high data requirements Very high computational requirements (especially with probabilistic sensitivity analyses) Limited by underlying model structure (e.g. CRA or Markov)	Kypridemos et al. (2017)[6]; Huang et al. (2019)[49]

CRA, comparative risk assessment. Information in table synthesized from Briggs et al. (2006), Briggs et al. (2016) and Emmert-Fees et al. (2021).

In this review, we cover the main SM approaches—from rather simple to highly complex—that are applied in the evaluation of nutrition and physical activity policies (table 3). An extensive discussion of SM for public health policy evaluation is available in Briggs et al. (2006), Briggs et al. (2016) and Emmert-Fees et al. (2021).

Comparative risk assessments (CRAs) are usually relatively simple cohort models, stratified by socio-economic and demographic groups, without explicitly accounting for time (table 3).[46,45] First, risk factor and disease distributions are projected over the simulation period. In a second step, the effect of different policy scenarios on these projections is specified using population impact fractions to simulate outcomes.[7,50]

Markov state-transition models, particularly in combination with proportional multi-state life tables, are widely applied (table 3).[8,48,51,52] Compared to CRAs, they explicitly model a population, often stratified in different age-sex-specific cohorts, over time. Markov models further implement explicit health states (e.g. healthy, sick and dead) between which cohorts transition proportionally, governed by epidemiological parameters, such as incidence, prevalence and case fatality rate.[41,47]

Microsimulation methods have become more common in recent years and are not a model type but rather a powerful technique that can be used within different modelling frameworks and embodies stochastic and dynamic components (table 3).[14,53] In microsimulations, individuals with their own demographic, socio-economic and health profile are simulated over time instead of homogenous cohorts. Individual probabilistic health and disease trajectories are estimated based on risk estimates (the stochastic component) and updated sequentially over discrete time steps (e.g. years) while retaining all individual-level information (the dynamic component).

Beyond the types of SM discussed, there are other approaches and techniques each addressing specific analytical and contextual considerations, such as agent-based models, system dynamics models and discrete-event simulations, which are not yet widely used for the evaluation of nutrition and physical activity policies, though.[7,54–56]

Conceptualization of models and required input data

Irrespective of the SM approach, four key interdependent components are needed to simulate the impact of nutrition and physical activity policies: (i) the level of complexity chosen to model risk factor–disease relationships; (ii) information on the (causal) relationship between risk factors, health and economic outcomes; (iii) demographic, socio-economic and epidemiological data; and (iv) the proposed mechanisms of policies.[8]

Most SM evaluations of nutrition policies rely on proximal risk factors, such as body mass index (BMI) and blood pressure, to estimate long-term NCD outcomes.[8,57] While this is often a necessary simplification due to data requirements, evidence suggests that dietary quality, food processing and the food-specific combination of micronutrients may be equally important in the aetiology of disease. Currently, much of this complexity is not reflected in SMs.[58] Correspondingly, it is essential to acknowledge differential effects of volume and intensity of physical activity when evaluating respective policies.[59]

Depending on the complexity of the model, the most important input for the simulation is the quantification of all explicitly included pathways between risk factors and outcomes. One challenge is that these are often only available as associations (i.e. non-causal) from non-randomized observational studies, potentially subject to unobserved confounding. This issue has been particularly discussed in nutritional epidemiology.[60,61]

Another central component of SMs is context/population-dependent demographic, socio-economic and epidemiological data. This includes prevalence and incidence data for diseases included in the model, as well as individual-level data on dietary intake and physical activity, particularly for microsimulations.[8,57] Yet, many countries lack high-quality disease surveillance systems and national surveys needed to parameterize very complex models.

Understanding the actual mechanism of the policy under consideration including relevant externalities is crucial to integrate policy effects into SMs. This includes information (e.g. from QEM) on heterogeneous policy effects across sub-populations (e.g. sex, age, ethnicity and income), leading to differentiated simulation parameters, compensatory behaviour in response to the respective policy [e.g. change in snack consumption after introduction of sugar-sweetened beverage (SSB) tax], spatial aspects of policies (e.g. household and out-of-home consumption) and distributional effects to assess impacts on health inequalities.[62]

Challenges and future directions

Two features are key to the implementation of SMs: (i) 'validation' and (ii) 'transparency'.

The results of SM applications can only be as good as the model structure and input parameters. Model 'validation' is therefore essential for high-quality simulation-based impact evaluations. Validity dimensions include 'input data validity' (e.g. relative risks for disease, policy effects etc.), the 'validity of the computational implementation' of the model (e.g. code review) and its ability to predict data that was not used in building the model, such as national survey and surveillance data on risk factors and disease outcomes ('external predictive validity').[63–66] However, simulated policy impacts are more difficult to validate as usually no observed data for comparison exists.

Due to the complexity of SMs, their assumptions and amount of data sources, it is crucial to 'transparently' provide information on results and methods for critical assessment. It is recommended to clearly communicate assumptions and publish lay summaries, detailed technical descriptions and computer code in Supplementary materials or online repositories.[65,67] Addressing 'validity' and practicing 'transparency' is crucial to assure trust by policymakers.

General challenges, which should be considered include: (i) simulations over many years into the future are subject to secular trends, socio-cultural disruptions and unforeseen behavioural changes;[38] (ii) differential dietary behaviours along socio-economic gradients are important to analyze equity impacts;[8,68] and (iii) dietary behaviour is shaped by factors beyond health and systems thinking ideas could be incorporated into SMs to help determine non-health sector impacts of dietary policies (e.g. economy, education etc.).[54]

Future efforts to improve simulation modelling of nutrition and physical activity policies should aim to disentangle the direct, indirect and total effects of diet on health including environmental, behavioural and socio-cultural dimensions to more accurately estimate long-term policy impacts. Further, the influence of regional variation in food environments and consideration of out-of-home food intake may be another avenue for improvement.

Particularly, synergistic environmental impacts of nutrition and physical activity policies are of high relevance and may further increase stakeholder relevance across non-health sectors following a health-in-all-policies approach.[69,70]

Discussion

QEM and SM can exploit valuable complementarities to inform policy makers on the impact and implications of different policy scenarios.[4] Whereas QEM provide a robust way to evaluate the effect on selected (and mostly intermediate) outcomes of policy measures implemented in the past, SM provide a framework to generate projections of the wider and longer-term implications of policy scenarios, potentially including combination of policies that have not been jointly implemented before.[4]

We propose that evidence from QEM, RCEs, non-experimental epidemiological studies and SM should be understood as part of an

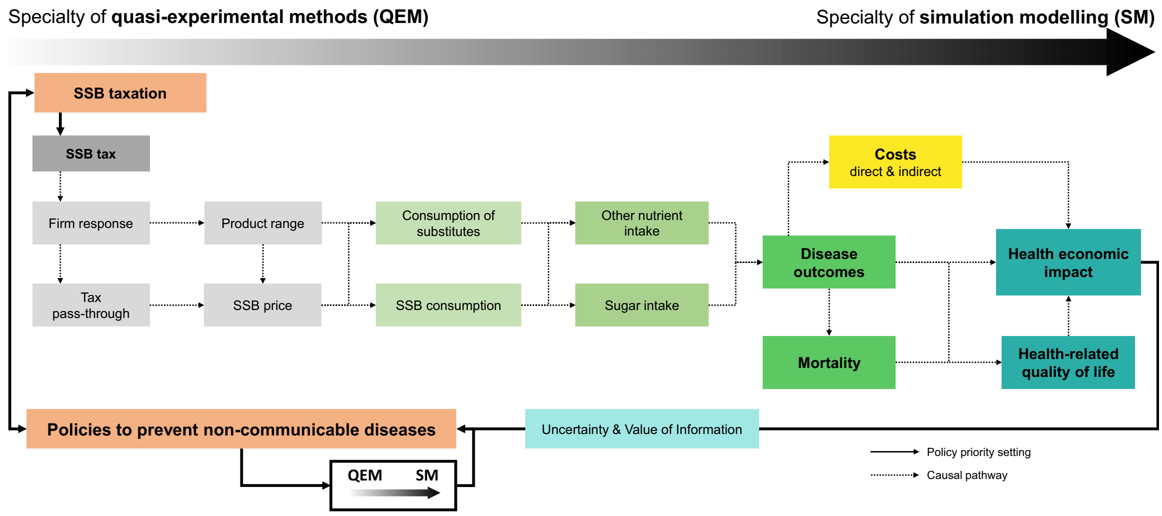

Figure 1 Exemplary policy evaluation and evidence cycle in the evaluation of a hypothetical tax on SSBs. SM, simulation modelling; SSB, sugar-sweetened beverage; QEM, quasi-experimental methods. Logic model of policy evaluation evidence cycle synergistically combining quasi-experimental studies and simulation modelling to inform policymaking

evidence cycle for policy evaluation in which each method has its specialty and estimates from QEM can be used as inputs for the mathematical relationships in the SM, which help to identify, compare and prioritize outcomes, policy scenarios and impact dimensions. These might then in turn be subject to evaluation in QEM studies after a policy decision was made.

Figure 1 visualizes the nature of this evaluation cycle for an exemplary tax on SSBs, as introduced in several jurisdictions around the world.[71]

In this context, QEM can provide evidence of the tax impact on: (i) firm response (product range and possible reformulations, tax pass-through and price);[72–76] and (ii) consumer response (including substitution patterns to other beverages and foods, at-home and out-of-home)[77] and, potentially sugar and other nutrient intakes.[78,79] One further key input needed in SM that QEM can provide are heterogeneous policy responses across firms and population sub-groups (e.g. CATE estimates).[80]

However, the estimation of intermediate and long-term health effects induced by changes in sugar and nutrient intakes through QEM is unfeasible, due to the lack of adequate longitudinal health data and the requirement for timely evaluations in policy making.[4]

SM approaches provide a solution to this challenge. They build on available survey data and the results of observational and QEM studies and, in the evaluation of an SSB tax, can translate changes in sugar intake and energy intake via established energy balance equations into changes in e.g. BMI.[81] Using the causal link between BMI and other risk factors SM calculate population health trajectories of relevant NCDs, such as type 2 diabetes, cardiovascular disease and cancer.[49] Ultimately, SM can project the expected long-term health and economic consequences of the SSB tax under consideration and compare alternative policies and taxation scenarios.[4,7,39]

Recent advances in causal inference for epidemiology emphasize the importance of integrating the plurality of methods for policy evaluation and have the potential to further strengthen the importance of QEM for public health simulation modelling.[82,83] Furthermore, when the SM framework is grounded in systems thinking and formalized within a logic model, it can provide qualitative guidance on the priorities for additional QEM studies for those parameters with insufficient evidence.[4] In the future, highly complex simulations, may model pathways from the consumer to health and non-health sectors to evaluate policies. Here, the method of value of information analysis—a technique that assesses the expected gain from reducing uncertainty in key parameters—could even be used to prioritize the estimation of model input parameters within a formal economic framework.[41]

Conclusion

QEM and SM have distinct strengths and limitations as standalone frameworks to estimate the impact of nutrition and physical activity policies. This integrative review analyzed a selective list of critical elements and assumptions to be considered when implementing these methodologies, and proposes to synergistically combine QEM and SM to overcome their limitations.

Below, we summarize the main lessons drawn:

- Assumptions behind models must be transparent and credible. This implies rigorous testing whenever possible, and validation through recognized robustness checks and sensitivity analyses.
- Nutrition and physical activity policies may act rapidly on behaviours, but the health effects may only become apparent in the longer term. QEM are a powerful tool to identify immediate causal effects, SMs are a better suited to project these behavioural changes into long-term outcomes.
- The growing interest in targeted policies and the variability in individual response, call for the application of QEM and SM to allow for heterogeneous responses, and consider the distribution of impacts across different population sub-groups.
- The implementation of multi-component lifestyle policies is a major challenge for QEM to elicit the contribution of individual measures. However, their joint application with SM has the potential to generate new evidence on the effectiveness of multi-component policies.

Finally, the evolution in methods for policy impact evaluation is closely related to the availability of adequate data. Until recently, the application of QEM and SM to nutrition and physical activity policies has been hindered by limitations in the quality and quantity of (longitudinal) data. Novel data technologies can help generate new evidence, and extend the toolkit for policy evaluation.

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Data availability

No new data were generated or analyzed in support of this research.

Key points

- Quasi-experimental methods are useful to identify short-term causal effects of nutrition and physical activity policies.
- Simulation models can be used to project the long-term health and economic impacts of nutrition and physical activity policies.
- Quasi-experimental and simulation modelling methods have strengths and intrinsic limitations as standalone frameworks.
- Combining the strengths of both approaches synergistically can lead to a more comprehensive approach to public health policy evaluation.

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B. Additional manuscripts

B.1. The demand for non-alcoholic beverages and implications for SSB taxation in Germany

Bibliographic information:

Title:	The demand for non-alcoholic beverages and implications for taxation of sugar-sweetened beverage taxation in Germany
Authors:	Matthias Staudigel*, **Karl M. F. Emmert-Fees***, Michael Laxy, and Jutta Roosen
Year:	2024
Status:	In preparation for submission to *Food Policy*[§]

Summary of methods and results:[‡¶]

The first objective of the conducted study was to estimate the demand for several categories of non-alcoholic beverages across households with different income levels with an economic demand model. The second objective was to estimate the purchasing and consumer welfare effects of a 20% price increase due to a tax on sugary drinks including SSBs, fruit juice and flavored milk.

We used data from 21,636 households participating in the two most recent waves of the German ICS (*Einkommens- und Verbraucherstichprobe*), which is a representative household consumption survey conducted every five years. Households report their income, expenditure and purchase quantities for various commodities including food and beverages. Specifically, we used information on the non-alcoholic beverage categories *flavored milk*, *plain milk*, *water*, *SSBs*, *fruit juice*, and *coffee & tea*. To stratify households by income terciles we adjusted incomes using the Organisation for Economic Co-operation and Development (OECD) equivalence scale. Because the data did not contain exact prices, we adjusted the resulting unit values for endogeneity using sociodemographic proxies for quality effects. We also adjusted expenditures shares for censoring by correcting them with category-specific purchase probabilities estimated using probit models. Conditional price and expenditure elasticities of the non-alcoholic beverage categories were estimated with a linearly approximated AIDS which was implemented using a seemingly unrelated regressions approach. Using the resulting elasticities, we simulated the purchasing and consumer welfare effects (compensating variation[†], tax revenue per month, tax share of monthly income) of two SSB taxation scenarios that lead to a respective 20% price increase of (1) SSBs or (2) SSBs, fruit juice, and flavored milk.

We found that German households spend on average 6.8% of their monthly budget on food and beverages. For low-income households this proportion was substantially higher (11.4%) than for their high-income counterparts (5%). With 17.9l per month, SSBs were the second most purchased

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[‡]We explicitly do not provide references in this short summary and refer to the respective publication.

[¶]The supplementary material/appendix to this additional manuscript is not included in this dissertation for brevity and available from the first author Karl M.F. Emmert-Fees via Email to karl.emmert-fees@tum.de.

[†]The compensating variation is a measure of welfare loss in economics and denotes the amount of money a consumer would need to be compensated with to retain their original utility after changes in the market.

non-alcoholic beverage after water (34.4l) and accounted on average for 27.6% of the non-alcoholic beverage expenditure. Purchasing probabilities and amounts were generally similar across income levels and households purchased around 8.3l of juice and 1.8l of flavored milk per month. Our demand analysis showed that the demand for sugary beverages was more elastic compared to other non-alcoholic beverages (oPE $<$ -1) particularly among low- and middle income households. These findings were largely compatible to other studies albeit we identified weaker substitution relationships between sugary beverage categories. This partially refutes concerns about meaningful substitution in light of price changes (for example due to a tax). However, we did not consider other sugary products such as sweets in our analysis which was also limited by product aggregation levels in the ICS. As such we were for example unable to distinguish non-caloric soft drinks from SSBs. According to the simulated scenarios a 20% price increase for sugary beverages would result in 3.4l less SSBs purchased per month (scenario 1) and an additional reduction in the purchasing of juice (-1.7l) and flavored milk (-0.3l) in scenario 2. From a public health perspective, these are meaningful reductions and comparable to international estimates. However, actual declines in sugar consumption after the introduction of SSB taxes, despite being harder to measure, are usually lower. Particularly high-income households would react less to price increases (-1.5l SSBs in both scenarios). Depending on the scenario, the estimated average welfare loss was between €0.8 and €1.5 per household per month and around 30% above average for high-income households. Conversely, the share of a potential tax in monthly household income was consistently twice as high for low- compared to high-income households.

Our study indicated that SSB taxation in Germany would be regressive. However, because health gains would be concentrated among low- and middle-income households, such a tax could in fact reduce health inequalities.

Title: The demand for non-alcoholic beverages and implications for sugar-sweetened beverage taxation in Germany

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Abstract

Due to their high sugar content, sugar-sweetened beverages (SSBs) have been identified as an important contributor to the global epidemic of obesity which poses a large health and economic burden on individuals and social care systems. To reduce their intake, several countries have implemented taxes on SSBs. In Germany, the demand for non-alcoholic beverages has not been analyzed and the potential consumer welfare effects of SSB taxation across income categories are unknown. We used two waves of a nationally representative household consumption survey to estimate the demand for non-alcoholic beverages in Germany using an economic demand model stratified by income. We then simulated two scenarios: (1) 20% added value tax on SSBs, and (2) 20% added value tax on SSBs, fruit juice, and flavored milk. We find that the demand for SSBs, fruit juice, and flavored milk is comparably elastic, particularly among low- and middle-income households. A 20% added value tax on SSBs would reduce the average monthly amount purchased per household by around 3.4 liters. High-income households would only reduce their SSB purchasing by 1.5 liters. Including fruit juice and flavored milk in the tax would lead to small additional effects. Depending on scenario, the average monthly welfare loss was €0.8 to €1.5 per household and substantially larger among high-income households. In contrast, the tax burden was consistently twice as large for low- versus high-income households. SSB taxation in Germany would be regressive but could help reducing health inequalities as sugar reductions are concentrated among low- and middle-income households.

Keywords

Food policy; Taxation; Price elasticity; Sugar-sweetened beverages; Non-alcoholic beverages; Demand modeling

Introduction

Overweight and obesity place a significant health and economic burden on societies due to various detrimental health consequences such as type 2 diabetes, hypertension, dyslipidemia, cardiovascular disease (CVD), and certain cancers [1]. In 2022, the global prevalence of obesity was estimated to be 18.5% for women and 14% for men [2]. The obesity rate in Germany is about 19% for women and men, respectively, according to the most recent estimates from 2020 [3]. Additionally, data from epidemiological surveillance systems and projections consistently indicate that the prevalence of obesity across countries is increasing and is very likely to increase further [2].

Overweight and obesity are also recognized as an important driver of global socioeconomic health inequalities and is patterned along a social gradient with higher rates in more disadvantaged population groups characterized for example by poverty, lower educational level and/or lower occupational class [4,5]. In Germany the difference in obesity prevalence between the highest and lowest income groups is about 5%-points for men and 15%-points for women [6]. Overall, these differences are related to the societal patterns of obesity determinants, such as unhealthy diets, low levels of physical activity, living conditions, parental obesity, parenting behaviors and psychosocial stressors [1,7,8].

The individual health burden caused by obesity has manifold additional negative consequences for society, such as for the economy and health and social care systems [9–11]. In 2019 the global economic burden of overweight and obesity through related healthcare costs and productivity losses was estimated to be about 2.2% of the global Gross Domestic Product (GDP) [9]. Similar figures have been reported for Germany where the total economic burden of obesity was estimated to be around €63 billion (~ 3% of GDP in 2010) [12].

Unhealthy dietary patterns, consisting of often highly processed foods high in salt, sugar, and fat, are among the most relevant determinants of obesity [13,14]. Particularly the consumption of sugar-sweetened beverages (SSBs), often defined as beverages containing caloric sweeteners such as sucrose, high-fructose corn syrup or fruit juice concentrates, has been identified as a key driver for weight gain due to their high content of liquid calories [15,16]. Importantly, unhealthy diets in general, and SSB consumption in particular, are more common among disadvantaged population groups increasing dietary risk and partially driving socioeconomic inequalities in obesity [17–20].

Beyond their effect on weight gain, high levels of sugar intake are associated with several NCDs, such as type 2 diabetes, coronary heart disease, and dental caries through direct mechanisms [15]. Hence, the World Health Organization (WHO) recommends that consumption of added sugar should not exceed 5% of total energy intake [21]. However, in most countries, including Germany, actual added sugar consumption is far above this threshold [22,23].

SSBs are the main source of added sugar in global diets [15]. Reducing the consumption of SSBs is therefore widely recognized as an important target for public health policy to prevent obesity and reduce socioeconomic inequalities in health [13,24]. In recent years particularly pricing policies – in the sense of a Pigouvian health tax – aiming to increase the price of SSBs have been discussed and adopted by many countries globally [13,25]. Currently more than 60 countries and subnational jurisdictions have implemented SSB taxation which is also recommended by WHO [15,26,27]. The underlying economic rationale for taxing SSBs is that negative externalities, in the form of healthcare and societal costs resulting from the detrimental health effects of high added sugar intake, are corrected by increasing SSB prices towards the societal optimum [25,28,29]. It is further argued that the likely regressivity of SSB taxes – low-income households have a higher relative tax burden than high-income households – does not pose a problem because the societal burden of high SSB consumption is concentrated among low-income households who might see the largest health benefits [28,30]. From a public health perspective, taxation as a structural prevention approach is also preferred over other policies that require more individual agency, such as health awareness campaigns, as policies that require a high level of individual agency are typically more effective among the highly educated and thus threaten to even widen socioeconomic health inequalities [31]. Additionally, some argue that taxes aiming to reduce added sugar consumption also address internalities which consumers impose on their future selves under the assumption that preferences are inconsistent over time [27,28]. The relevance of internalities also carries particular importance for the interpretation of potential welfare losses resulting from health taxes [30].

Governments have followed different philosophies in the design of implemented SSB taxes with heterogenous implications for consumers and producers. Currently, most SSB taxes are specific excise taxes with a fixed tax rate per liter or excise taxes that are administered ad-valorem, which are simple to administer and collect [32]. However, while these tax designs aim to raise the average price of SSBs, they do not account for differences in product quality or sugar content within the same beverage category [32]. Conversely, in some countries the tax rate is based on sugar content in a linear or tiered fashion to avoid substitution with cheaper but equally sugary alternatives and to incentivize reformulation by producers (e.g. United Kingdom and France) [32,33]. Although implementation and collection of SSB taxes based on sugar content per liter is likely more complex, it ensures a better alignment of incentives [27,32].

Despite high burden of obesity, CVD and diabetes, Germany currently lacks a policy strategy to improve unhealthy diets on a population level [34]. In 2020, a comprehensive report by the scientific advisory board of the Federal Office for Agriculture and Food (SABAF) addressed this issue and outlined a national system-wide strategy for sustainable and healthy diets to combat obesity and reduce the carbon footprint of the German food system. This report specifically recommended the introduction of a tax on SSBs that increases linearly with sugar content [35]. Other German non-governmental organizations, research associations and health advocacy groups have made similar proposals [36,37]. However, until now, no tax on SSBs is enacted in Germany. Instead, since 2015, voluntary industry commitments with the aim to reduce sugar in beverages by 15% until 2025 are in place [38]. A recent evaluation has shown that these commitments indeed failed to achieve the targeted reductions [39,40].

Internationally, a large body of literature on the economics of SSB taxes and their ability to reduce consumption exists [25,27,41]. Previous studies have either *ex-ante* used economic modeling to estimate the expected change in SSB demand before the implementation of a tax or in contexts where no such policies exist, or *ex-post* assessed observed price and demand effects after their implementation [27,41,42].

Published *ex-ante* economic studies mostly applied the linearly approximated Almost Ideal Demand System (AIDS) following Deaton & Muellbauer (1980) [43] or its quadratic extension (QUAIDS) following Banks, Blundell & Lewbel (1997) [44] to estimate SSB demand parameters based on household consumption, individual transaction, or consumer panel data [30,45–56]. A review and meta-analysis of these applications from different countries estimated an SSB own-price elasticity of demand of around -1.3 [57]. Important implications from this literature are that 1) there is likely considerable heterogeneity of price elasticities with regards to subgroups within the broader category of SSBs, such as isotonic sports drinks, and that within category substitution (e.g., from high-caloric to low-caloric SSBs) may be relevant [30,48,58]; 2) substitution to other non-alcoholic beverage categories is likely to occur only on a small scale without offsetting overall reductions in sugar consumption or calorie intake [47–50]; 3) habit formation plays a role in beverage consumption choices and potentially follows different mechanisms depending on income [48]; and 4) preferences are heterogenous with respect to beverage consumption levels (lower own-price elasticity for high-consumers) and age (higher own-price elasticity for younger individuals) [30,45,46]. Multiple studies have also investigated changes in beverage demand stratified by social determinants of health, such as income. While the evidence is mixed with regards to differences in the SSB own-price elasticity across income strata these studies generally come to the conclusion that SSB taxation is, as expected, likely regressive because of low-income households spending a higher proportion of their income on SSBs [27,51,55,59]. However, the additional tax burden on low-income households is small in absolute terms and could be mitigated by accompanying policies, such as fruit and vegetable subsidization, to support these households [30,45,48,51–54,56]. Due to their higher consumption and obesity rates, low-income households could also be the prime beneficiaries of SSB taxation if internalities are indeed important [30].

The results from *ex-post* studies are largely consistent with those from *ex-ante* studies. A recently published systematic review and meta-analysis of *ex-post* studies synthesized price and demand outcomes of SSB taxation [41]. The authors estimated an overall tax pass-through to consumers of 82.2% (based on 46 estimates from 41 studies covering 18 policies) and an overall SSB own-price elasticity of demand of -1.59 (based on 35 estimates from 33 studies covering 16 policies) for a 1% change in price. No relevant impact on the consumption of untaxed beverages as well as no relevant substitution or cross-border shopping was identified [41].

The potential consumer reaction to a tax on SSBs in Germany across different income groups, the relevance of potential substitution to other non-alcoholic beverages, related welfare effects, and equity implications are unknown. Most recently, Peltner & Thiele (2021) used QUAIDS methods to estimate the demand for a comprehensive set of food groups based on market research household scanner data from 2011 [60]. However, in their analysis, beverages were not disaggregated into neither alcoholic and non-alcoholic beverages, nor other subgroups like SSBs. It is therefore not possible to derive implications of SSB taxation in Germany from these estimates. Yet, context-specific estimates of own- and cross price elasticities of SSBs and their potential substitutes are key to guide policy discussions about the implementation of a tax on SSBs in Germany. Further such estimates are highly relevant as input parameters for national health economic modeling studies with the objective to evaluate the long-term impacts of obesity prevention strategies including the taxation of SSBs [42,61].

In this study, we close an important evidence gap by estimating the demand for SSBs and other non-alcoholic beverage categories in Germany based on the most recent waves of the German Income and Consumption Survey ("*Einkommens- und Verbraucherstichprobe*") (ICS) in 2013 and 2018 using a linearly approximated AIDS. We then apply these estimates to simulate the changes in non-alcoholic beverage demand and welfare effects induced by 1) a 20% ad valorem tax on SSBs and 2) a 20% added value tax on SSBs, fruit juice and flavored milk. To assess equity implications and the potential regressivity of the proposed taxation scenarios we also conduct analyses stratified by terciles of equivalized household income.

Methods

The distinct methodological steps to derive demand parameters for non-alcoholic beverages and to assess the impact of SSB taxation scenarios on consumption and consumer welfare in Germany are detailed in the following sections. We first describe the used nationally representative household survey data. We then theoretically specify the linearly approximated AIDS. Next, we present our methods to recover quality-adjusted prices from unit values following Cox and Wohlgenant (1986) and describe the two-step estimation to adjust budget shares for censoring according to Shonkwiler and Yen (1999) [62,63]. Finally, we define the simulated SSB taxation scenarios in detail and describe our methods to derive demand and welfare effects of these scenarios using the estimated price and expenditure elasticities.

Household survey data

We use data from the two most recent waves of the German Income and Consumption Survey ("*Einkommens- und Verbraucherstichprobe*") (ICS) in 2013 and 2018 which is collected by the Federal Office of Statistics and can be accessed through the Federal Scientific Data Center (for details see: https://www.forschungsdatenzentrum.de/de/haushalte/evs). The ICS takes place every five years and is a population representative repeated cross-sectional study based on a quota sample of households which are the primary sampling unit. Participating households record detailed information about their income and expenditures across various commodities in a household book during one quarter of the year. In addition, during one month of the study a subsample keeps detailed records of their purchases of food and beverages, as well as tobacco products. To account for seasonality effects this subsample is rotated throughout the year across households. The data thus contains information on monthly quantities and expenditures per household for different commodity categories as defined by the Classification of Individual Consumption by Purpose (COICOP).

The ICS targets to interview a total of about 80,000 households resulting in a net sample of about 55,000 households. In the two ICS waves we used (i.e., 2013 and 2018) 11,648 and 10,562 households provided detailed records on food and beverage expenditures, respectively [64,65]. Thus, based on these two waves of cross-sectional data, we arrived at a combined final sample of 21,636 households after removing 574 observations which were outliers and households reporting not to have consumed any beverages.

For our demand analysis, we selected the aggregated monthly quantities and expenditures per household of the non-alcoholic beverage categories available in the ICS. These were *flavored milk* (e.g., banana milk, cacao), *plain milk*, *water*, *SSBs* (sparkling and still [e.g., iced tea]), *juice* (including fruit, citrus and vegetable juices), and *coffee & tea* (not including iced tea drinks, which are included under SSBs).

In the estimation and adjustment procedures for prices and expenditure shares, we further relied on a range of sociodemographic characteristics of the participating households that are available in the ICS. These included the net monthly household income, household size (including the number and age of children), the age, sex and occupation of the main earner, the number of employed household members and a geographic identifier based on German Nielsen regions. German Nielsen regions are defined as follows: 1) Hamburg, Bremen, Lower Saxony, and Schleswig-Holstein were summarized into one region; 2) Hessia, Rhineland Palatinate, and Saarland were summarized into one region; 3) Berlin, Brandenburg, Mecklenburg-Vorpommern, and Saxonia-Anhalt were summarized into one region; and 4) Saxonia and Thuringia were summarized into one region. Possible seasonality effects in non-alcoholic beverage purchases were addressed using average monthly temperature data obtained from the German Weather Service which was aggregated to Nielsen areas (i.e., region) [66]. We then matched the average reported temperature by year, month, and region to each household.

To assess differences in non-alcoholic beverage demand by income, we divided the sample into terciles of equivalized household income (i.e., low-income, middle-income, high-income), which we calculated using the OECD equivalence scale (1 for the first adult, 0.5 for a child ≤ 15 years of age and 0.3 for any other child and additional adult).

Demand modeling approach

To model demand for non-alcoholic beverages in Germany, we estimated a linearly approximated AIDS system according to Deaton and Muellbauer (1980) [43]. We followed the same overall procedures as Roosen et al. (2022) which estimated the effect of several meat taxation scenarios using German household scanner data [67]. We modelled the demand for the six non-alcoholic beverage categories as expenditure shares which allows for the introduction of constraints on adding-up, homogeneity, and symmetry. The expenditure share w_{ih} of household h in category i (1 = flavored milk, 2 = plain milk, 3 = water, 4 = SSBs, 5 = juice, 6 = coffee & tea) resulting from cost minimization is denoted as

$$w_{ih} = \alpha_i + \sum_j \gamma_{ij} \ln p_{jh} + \beta_i \ln(M_h/P_h) + v_{ih} \text{ for } i = 1, \ldots, 6 \quad (1)$$

where p_{jh} denotes the price of beverage category j paid by households h, M_h is the net equivalent household beverage expenditure of household h, α_i, γ_{ij}, and β_i are the estimated parameters and v_{ih} is the error term. As for the linear AIDS we used a linear approximation of the price index P_h which we defined as a corrected Stone-Laspeyres price index following Moschini (1995) [68]. This price index is given by

$$\ln P_h^S = \sum_{i=1}^{n} \overline{w_i} p_{ih} \quad (2)$$

We accounted for the theoretical constraints of demand (i.e., adding-up, homogeneity, symmetry) by imposing:

Adding-up: $\sum_i \alpha_i = 1,\ \sum_i \beta_i = 0,\ \sum_i \gamma_{ij} = 0$ (3a)

Homogeneity: $\sum_j \gamma_{ij} = 0$ (3b)

Symmetry: $\gamma_{ij} = \gamma_{ji}$ (3c)

Adjustment procedures and estimation

Adjustment of unit values

Because our data contained monthly aggregated household quantities and expenditures per non-alcoholic beverage category, our demand estimation relied on unit values (UVs). However, the use of UVs in demand analyses introduces bias because they represent exogenous price variation as well as household choices over a set of products with different quality attributes. We therefore adjusted UVs for quality effects following the procedure suggested by Cox and Wohlgenant (1986) [62]. Since quality characteristics are not observed in the data, we used several demographic and socioeconomic proxy variables (C_{ic}) to adjust UVs in each category i:

$$\ln UV_i = \delta_i + \sum_c \kappa_{ic} C_{ic} + e_i \quad (4)$$

where δ_i is an intercept, κ_{ic} is a vector with one coefficient per proxy variable and e_i is the error term. We modelled UVs as a linear function of the proxy variables household size, monthly net household income, occupation, age, and sex of the main earner, the number of employed household members, the number of children in the household across different age categories (<1 year, 1-3 years, 3-6 years, 6-12 years, 12-18 years), region and time [62]. Importantly, we did not observe missing values in the UV variables.

Using these models, we calculated adjusted UVs as the sum of the estimated constant $\widehat{\delta_i}$ and the residuals $\widehat{e_i}$ from equation (4). Because demand effects from consumers are captured by the proxy variables, the adjusted UVs represent variation due to supply-side factors. Appendix Table 1 shows the coefficients of the UV regression models.

Adjustment of expenditure shares

Because the AIDS system defined in equations (1) and (2) will result in biased estimates in the case of censoring (i.e., zero observations across households and product categories) we applied the approach suggested by Shonkwiler and Yen (1999) [63]. In this two-step approach, we first estimated the probability of households purchasing any product from a specific product category in a month using probit models. Here a binary indicator of any purchase in category i is modelled as a function of household characteristics, time, and regional variables. We used the same set of variables as for the UV adjustments above. Appendix Table 2 shows the coefficients of the estimated probit regression models.

In the second step, conditional on non-zero expenditures, the expenditure shares from equation (1) are corrected for censoring by the predicted probability density function ϕ_{ih} and cumulative distribution function Φ_{ih}, which are both derived from the category-specific probit regressions, to yield

$$w_{ih} = \Phi_{ih} \times \left[\alpha_i + \sum_j \gamma_{ij} \ln p_{jh} + \beta_i \ln(M_h/P_h)\right] + \theta_i \phi_{ih} + \varepsilon_{ih} \quad (5)$$

Endogeneity adjustment

In a final step we used a control function approach to adjust for potential endogeneity in the non-alcoholic beverage budget following Crawford et al. (2003) [69]. In the first stage. we therefore regressed the budget variable in the demand system $\ln(M_h)$ on total food expenditure as an instrument and a vector of household characteristics as controls. The coefficients of this regression are in Appendix Table 3.

We then used the predicted residuals from equation (5) $\widehat{\zeta_h}$ as an additional regressor in the final demand model together with controls for household characteristics and indicators of time and region to account for seasonality (φ_h). This yielded the following final demand model:

$$w_{ih} = \Phi_{ih} \times \left[\alpha_i + \sum_j \gamma_{ij} \ln p_{jh} + \beta_i \ln(M_h/P_h)\right] + \theta_i \phi_{ih} + \widehat{\zeta_h} + \varphi_h + \varepsilon_{ih} \quad (6)$$

Estimation and elasticity computation

The system described by equations (2) and (6) was then estimated using a seemingly unrelated regression approach for five of the six non-alcoholic beverage categories (*flavored milk*, *pure milk*, *water*, *SSBs*, *juice*). Parameters for the sixth category (*coffee & tea*) were retrieved from the constraints (3a) – (3c). To treat one category as auxiliary and retrieve the respective parameters via the theoretical restrictions is common practice in demand system estimation to avoid singularity. We checked the robustness of the estimated parameters by changing the auxiliary category and re-estimating the model (data not shown). The raw estimates of the demand model in equation (6) are in Appendix Table 4.

To compute stratified demand parameters by terciles of net equivalized household income, we repeated the same estimation procedure on the respective subset of the sample, excluding household income as a covariate. The results of the endogeneity adjustment outlined in equation (5) and the raw estimates from the demand model in equation (6) for these stratified analyses are in Appendix Tables 5-10.

Using the estimated parameters, the mean adjusted expenditure shares $\bar{w}$, and the purchase probabilities $\bar{\Phi}$ from the probit models, we calculated the compensated ε_{ij}^{*} and uncompensated price elasticities ε_{ij}, as well as the expenditure elasticities η_i, at the means of the sample with the formulas from Green and Alston (1990) [70]:

Expenditure elasticities: $$\eta_i = \bar{\Phi}_i \cdot \frac{\hat{\beta}_i}{\bar{w}_i} + 1 \quad (7a)$$

Uncompensated price-elasticities: $$\varepsilon_{ii} = \bar{\Phi}_i \cdot \left(\frac{\hat{\gamma}_{ii}}{\bar{w}_i} - \hat{\beta}_i\right) - 1 \quad (7b)$$

$$\varepsilon_{ij} = \bar{\Phi}_i \cdot \left(\frac{\hat{\gamma}_{ij} - \hat{\beta}_i \bar{w}_j}{\bar{w}_i}\right), \text{ with } k \neq j \quad (7c)$$

Compensated price-elasticities: $$\varepsilon_{ij}^{*} = \varepsilon_{ij} + \bar{w}_j \cdot \eta_i \quad (7d)$$

We obtained standard errors for the elasticities derived from the above equations (7a) – (7d) using bootstrapping with 5000 iterations following Krinsky and Robb (1986) [71].

Taxation scenarios

Using the estimated demand parameters, we simulated the consumer reactions to two hypothetical taxation scenarios: (1) a 20% ad valorem tax on SSBs (*Ad-Valorem Tax*), and (2) a 20% ad valorem tax on SSBs, fruit juice and flavored milk (*Extended Ad-valorem Tax*). These scenarios were, within the limits of the aggregated categories in the ICS, defined based on international guidance from the WHO and internationally implemented taxes [26,32]. Although fruit juice is internationally seldomly taxed, we included it as a potential target for taxation in the *Extended Ad-valorem Tax* scenario because juice consumption in Germany is relatively high, juices sometimes contain even more sugar than SSBs, and its health effects are thus controversial [72–74]. In our analysis, we were, however, not able to differentiate between diet soft drinks (i.e., soft drinks containing artificial non-caloric sweeteners such as aspartame) and SSBs, which might be relevant due to substitution effects under the assumption that diet SSBs remain untaxed [30,48,55].

For simplicity, we assumed in both scenarios that the tax would be implemented in a way that the price of the respective beverages would increase by 20%, thus disregarding considerations of pass-through by companies and retailers. We also explicitly do not consider where in the supply chain the tax would be levied. This is justified since we are only interested in demand side welfare effects. Supply side effects are outside the scope of this analysis. The scenarios are thus treated as generic average price increases that could in practice be achieved with various different tax designs. Due to the nature of our data, we were not able to analyze other tax designs, such as tiered SSB taxes (e.g., *Soft Drinks Industry Levy* in the United Kingdom) which can have both price and product reformulation effects. For example, to simulate taxes for which tax rates depend on SSB sugar content, a design that was also recommended by WHO and the scientific advisory board of the German Federal Office for Agriculture and Food, we would need information on the nutritional content of individual beverages purchased by each household that are not available in ICS [35].

Calculation of welfare effects

Using the same approach as Roosen et al. (2022) we followed Säll and Gren (2015) and Säll (2018) to derive demand, budget, and welfare effects of the taxation scenarios based on the estimated AIDS [67,75,76]. We used the uncompensated price elasticities to simulate absolute and relative changes in purchased quantities of non-alcoholic beverages under the two scenarios specified above (i.e., *Ad-valorem Tax* and *Extended Ad-valorem Tax*) using household-level adjusted UVs. We here assumed a consumer tax τ which represents the difference between prices before and after the tax introduction indicated by a superscript in the price variable ($\tau = p_{id}^1 - p_{id}^0$). In our case the category-specific prices after the introduction of the tax are defined as $p_{id}^1 = 1.2 \times p_{id}^0$.

We calculated the relative change (%Δ) from before to after the tax in purchased quantities of non-alcoholic beverage category *i* from the own- and cross-price effects as

$$\%\Delta x_{ih} = \sum_{j=1}^{6} \varepsilon_{ij} \%\Delta p_{jd} \tag{8}$$

The new absolute purchasing levels for category *i* by household *h* after the tax, x_{ih}^1, can thus be derived from the consumption level before the tax x_{ih}^0. Accordingly, the changes in household expenditure (*ΔExp*) considering changes in demand under the tax τ can be computed as

$$\Delta Exp_h = \sum_{i=1}^{6} [(p_{id}^1 \times x_{ih}^1) - (p_{id}^0 \times x_{ih}^0)] \tag{9}$$

The tax revenue (*TR*) per household and month can be derived as the price change multiplied by the new purchase quantity and is thus calculated as

$$TR_h = \sum_{i=1}^{6} [(p_{id}^1 - p_{id}^0) \times x_{ih}^1] \tag{10}$$

Finally, we calculated the compensating variation (*CV*) of the price change under tax τ as a measure of consumer welfare effects. The *CV* is defined as the amount of money needed (i.e., the compensation) to keep utility constant when prices change. Based on Azzam and Rettab (2012) [77] we computed

$$CV = \sum_{i=1}^{6} p_i^0 x_i^0 \left(\frac{dp_i}{p_i^0} + \frac{dx_i^*}{p_i^0} + \frac{dp_i}{p_i^0} \times \frac{dx_i^*}{p_i^0} \right) \tag{11}$$

where p_i^0 and x_i^0 represent prices and quantities before the tax and dx_i^* denotes the compensated change in demand under the tax based on the compensated elasticities from equation (8d).

Results

Characteristics of the sample

The socio-demographic characteristics of the analysis sample are given in Table 1. Overall, children are present in 34% of households, the majority of which is between 6 to 17 years of age. There are only minimal differences across household income categories with a slightly higher overall household size due to more children in the middle-income category. The mean age of the main earner across households is around 53 years with no observed differences based on household income. In 61% of participating households a person of male sex is the main earner. The overall distribution of main earner occupations in the sample shows that around 5% are self-employed, 8% are civil servants, 41% white-collar workers, 8% blue-collar workers, 4% unemployed, 30% retired, 3% students, and 1% other non-employed. In the high-income category the share of civil servants and white-collar workers is higher and the share of students lower; and in the low- and middle-income categories the share of unemployed persons and blue-collar workers is higher and the share of retired persons lower.

Across all households on average one household member is employed and the number of employed household members is higher among high-income households. We find that the regional distribution of households in the data mirrors regional income inequalities in Germany since the share of low-income households is lowest in least deprived regions (e.g., Baden-Württemberg and Bavaria) and highest in areas with higher deprivation (e.g., Saxonia and Thuringia) [78]. The average overall net household income in the sample is €3,750 per month, of which households spend on average around €256 (~6.8%) on food and beverages. Among the households in the lowest income tercile (i.e., bottom 30% of the income distribution), the average net household income is €1,750 per month (€200 or ~11.4% spent on food and beverages); in the middle tercile it is €3,340 per month (€267 or ~7.8% spent on food and beverages); and in the highest tercile it is €6,050 per month (€301 or ~5.0% spent on food and beverages).

Description of the demand for sugar-sweetened and other non-alcoholic beverages

Purchase probabilities across household income tertiles were very similar (Appendix Table 11). A descriptive summary of purchased quantities (without zero observations/only purchasing households), unadjusted and adjusted unit values, expenditures, and budget shares (among households purchasing any product in the respective category) for the six non-alcoholic beverage categories is given in Table 2. Households on average purchase around 1.8 liters (*l*) flavored milk, 9.7*l* of plain milk, 34.4*l* of water, 17.9*l* of SSBs, 8.3*l* of juice and 1.2 kilograms (kg) of coffee & tea per month. For the categories flavored milk, SSBs and juice the coefficient of variation is >1 indicating larger heterogeneity in purchasing compared to the other categories. Taking the average household size into account this amounts to 101.3*l* of SSBs and 47*l* of juice purchased per person per year. Factoring in waste and non-purchasing households, these figures are similar to estimates of SSB and juice consumption in Germany published by industry associations but lower than reported in epidemiological studies [72,73,79]. After coffee & tea for which households on average spend €13.1 SSBs are responsible for the second highest monthly expenditure on non-alcoholic beverages at €12. This results in an average monthly SSB budget share among non-alcoholic beverages of 27.6%.

The descriptive summaries stratified by household income show that there is variation in purchased quantities for some beverage categories (Table 2). Households with high and middle incomes purchase more water, coffee & tea, and juice than their low-income counterparts. Unexpectedly, households with a middle income purchase more SSBs than both low- and high-income households, of which the latter purchase the fewest. The comparison of unadjusted and adjusted unit values shows consistent quality gradients by income. For example, low-income households pay around €0.89 per liter of SSB, whereas middle- and high-income households pay €0.98 and €1.11, respectively. These differences largely diminish after adjustment. Although average expenditures across all six categories are the highest among high-income households, budget shares are almost always the lowest in this group.

Demand elasticity estimates for sugar-sweetened and other non-alcoholic beverages

Conditional uncompensated and compensated price elasticities together with expenditure elasticities, calculated based on equations (7a) – (7d), are depicted in Table 3. We find that uncompensated own-price elasticities are all highly statistically significant with p-values below 0.001. For plain milk, water, and coffee & tea, which are foods that are consumed daily by most people, values are between −0.79 and −0.80 indicating that demand for these beverages is comparably inelastic. Conversely, uncompensated own-price elasticities for flavored milk, SSBs and juice are smaller than −1, except for SSBs with a value of −0.96, indicating a more elastic demand. This is expected since these categories contain products that are usually viewed as non-essential beverages consumed for pleasure but in contrast to notions that consumers may be addicted to the contained sugar. Uncertainty for uncompensated cross-price elasticities is high. They show complex substitution patterns, which do however not reach statistical significance. We observe a clear pattern for the non-essential beverage categories flavored milk, SSBs and juice which serve as mutual substitutes for each other. Consistent with other studies we also find a small substitution effect between SSBs and plain milk [57].

The estimated conditional expenditure elasticities are largely consistent with the notion of regularly consumed and non-essential non-alcoholic beverages (Table 3). The respective values for plain milk (0.907) and water (0.925) are the lowest among the included categories. Conversely, consumers react more strongly to expenditure increases with regards to the purchasing of SSBs (1.032) and juice (1.053).

The uncompensated and compensated own-price elasticities as well as expenditure elasticities stratified by net equivalent household income terciles are presented in Table 4. There is a large difference in the own-price elasticity for SSBs across household income: Low- and middle-income households show a quite elastic demand with values of around −1.2, while the demand for SSBs of high-income households is very inelastic at around −0.4. We further find that low-income households react stronger to price increases in flavored milk and coffee & tea compared to middle- and high-income households. Expenditure elasticities per category are broadly similar across income strata (Table 4).

Consumption and welfare effects of sugar-sweetened beverage taxes

The mean absolute and relative changes in consumption of non-alcoholic beverages under the SSB taxation scenarios are given in Table 5. As price elasticities denote relative changes, consumption changes are only meaningful for those households purchasing the respective category.

For the *Ad-Valorem Tax* scenario, in which only SSBs are taxed, we find an average reduction of SSB consumption of around 19.1%, which translates to 3.4*l* of SSBs per household per month. The decline is highest among low- and middle-income households which reduce their consumption by 22.8% (4.0*l* of SSBs) and 24.9% (4.8*l* of SSBs) respectively. High-income households would have the lowest reduction at 8.6% (1.5*l* of SSBs).

Although there are substitution effects to non-essential beverages following from the estimated cross-price elasticities between beverages, these would translate to only minimal absolute changes in consumption. For example, the simulated *Ad-Valorem Tax* would lead to an increase of juice and flavored milk consumption of 0.7% and 1.4% respectively across all households. This translates to 26 milliliters (*ml*) more juice and 62 *ml* more flavored milk per household and month consumed, which is negligible. Despite some heterogeneity across household income strata, the general picture remains the same. We also observe that there are heterogeneous cross-price effects for water. Middle-income households would barely change their water consumption under the *Ad-Valorem Tax*. But lower-income households would buy 2.3% (0.7*l*) more and high-income households 2.8% (1.1*l*) less water. This could be explained by lower income households substituting SSBs with water while more affluent households reduce consumption of more expensive water brands considering increased SSB prices (see also Table 2).

An extension of the tax to fruit juice and flavored milk (*Extended Ad-Valorem Tax*) would lead to reductions in monthly SSB consumption across households comparable to the *Ad-Valorem Tax* (Table 5). However, as expected, there would be additionally considerable relative reductions for juice and flavored milk. Households, irrespective of their income, would reduce their monthly juice consumption by around 21% translating to 1.7*l* per household. Similarly, flavored milk consumption would decrease on average by 16.5%. However, since the latter category is overall rarely consumed, this relative reduction translates to small absolute changes of about 300 *ml* per household and month on average. We observe that also an *Extended Ad-Valorem Tax* would lead to increased water consumption among low- and middle-income households and reductions among high-income households.

Welfare effects of the two SSB taxation scenarios are shown in Table 6, where we report expenditure changes, welfare changes (CV), the tax revenue, and the tax share in % of the net income across all households per month. The *Ad-Valorem Tax* would lead to very heterogenous changes in expenditure across households. On average we observe decreased expenditures of around €0.31. However, high-income households would in fact increase their expenditure by €0.22, which is likely due to their inelastic response to changes in SSB prices. Expenditure changes are more homogenous in case of an *Extended Ad-Valorem Tax* which would lead to a large reduction of about €1 among middle-income households to about €0.24 among high-income households.

Welfare effects, measured as the CV, are on average €0.8 and €1.5 for the *Ad-Valorem* and *Extended Ad-Valorem Tax*, respectively, but distributed unequally across households. In both taxation scenarios, high-income households have the highest welfare loss of €1.3 (*Ad-Valorem Tax*) and €2.2 (*Extended Ad-Valorem Tax*). Overall, welfare losses are higher under an *Extended Ad-Valorem Tax* as more categories are subject to the tax. The monthly tax revenue per household mirrors these results. On average, the tax revenue is €1.3 in case of the *Ad-Valorem Tax* and €2.4 in case of an extended tax. Additionally, tax revenues increase with household income as the response to price changes of SSBs becomes less elastic. Across all households, the share of the *Ad-valorem Tax* is 0.04% of the net income, compared to 0.08% for the *Extended Ad-Valorem Tax*. Tax shares decrease with household income, and we thus find that both taxation scenarios would be regressive. For example, under an *Extended Ad-Valorem Tax*, low-income households would spend about 0.1% of their monthly income on the tax compared to 0.05% for high-income households.

Discussion

In this study, we combined two waves of a large nationally representative household consumption survey to estimate the demand for SSBs and other non-alcoholic beverages in Germany accounting for censoring, quality effects, and seasonality. To assess heterogeneity, demand parameters were estimated for the full sample and stratified by household income. We then used the estimated demand elasticities to simulate the consumption and welfare effects of two hypothetical scenarios of a 20% ad-valorem tax on beverages containing large amounts of free sugars. In the first scenario only SSBs were taxed (*Ad-valorem Tax*) and in the second we additionally considered fruit juice and flavored milk to be part of the tax (*Extended Ad-Valorem Tax*).

We found that the uncompensated own-price elasticity of demand for non-alcoholic beverages in our sample overall varied between −1.1 and −0.8. Elasticities were higher for beverages often consumed for pleasure (i.e., flavored milk, fruit juice, SSBs) compared to other non-alcoholic beverages (e.g., plain milk, water, coffee & tea). Compensated elasticities were considerably smaller for all categories, except flavored milk, indicating strong expenditure effects. The estimated cross-price effects revealed clear substitution patterns between flavored milk, fruit juice, and SSBs, which albeit were of small size and not statistically significant. The heterogeneity of demand parameters stratified by household income was considerable and particularly for SSBs, the demand among high-income households was very inelastic.

There are no comparable studies on non-alcoholic beverage demand in Germany. However, the estimated elasticities are similar to existing international studies and settings [30,45–56]. The only recent German study that estimated demand parameters across a large number of food groups reports an own-price elasticity of around −1.1 for all beverages (alcoholic and non-alcoholic) [60]. Direct comparisons with international studies across beverage categories are complicated by different data sources, methods, and product aggregation levels. In our study, the own-price elasticity of SSBs was around −1, which is comparable to other estimates based on observed price changes after implemented SSB taxes (*ex-post* estimates) and demand models like ours (*ex-ante* estimates) [30,41,45–56]. However, compared to these studies we find lower substitution effects from SSBs to other sugary beverages, such as fruit juice. Considering the breadth of the SSB category in our study, these could be masked by differential substitution patterns for SSB sub-categories like energy drinks or diet SSBs. Although we cannot observe these effects due to the level of aggregation in our data, it has further to be noted that the results from other studies are inconclusive about whether diet SSBs are indeed an important substitute for SSBs [30,48,55].

The existing literature is also mixed with regards to the own-price elasticities of sugary drinks across household income levels. Consistent with some studies we observe that the demand elasticity for SSBs for high-income households is lower than for their low- and middle-income counterparts [51,55]. However, others find the opposite or report very similar elasticities across income strata [59]. In our sample, households consume roughly similar amounts of SSBs irrespective of their income and have the same purchasing probabilities. Although this is unintuitive considering a likely higher health literacy among affluent households, the above finding could be explained by rather homogenous preferences over income groups. In the face of higher prices under a tax, low- and middle-income households reduce SSB expenditure while high-income households still can afford these products. However, these findings are inconsistent with studies that find the demand for SSBs among households with a high consumption of these beverages, which also often have a lower income, to be comparably inelastic [45,46]. Thus, the joint effect of household income and SSB consumption levels in Germany should be further explored.

Our simulated scenarios indicate that a taxation of SSBs could lead to meaningful reductions in SSB consumption. In the 20% *Ad-Valorem Tax* scenario we estimate a decrease of on average about 3.4*l* SSBs per purchasing household per month which is concentrated among low- and middle-income households due to their higher price elasticity. Assuming a sugar content of 10 grams (g) per 100*ml* and a proportion of diet SSBs of 30% this implies a reduction of 238g from SSB-related sugar per purchasing household per month which translates to roughly 28g of sugar per capita per week (≈ 1 can of SSB) [80]. This is only the direct effect without considering substitution, which however is minimal as described above and thus does not substantially alter the total net effect. In the *Extended Ad-Valorem Scenario* the overall reduction in sugary beverages and sugar consumption is even higher due to the greater number of taxed beverage categories. The additional benefits are, however, comparably small due to the overall lower consumption levels of fruit juice and flavored milk.

These results are in line with scenario simulations from other (*ex-ante*) demand modeling studies. Dharmasena and Capps (2012) found a reduction of 1.5*l* per capita and month for a

20% ad-valorem tax at full pass-through, which is very similar to our results accounting for the average household size. Zhen et al. (2011) reported that a half-cent per ounce (≈28.4*ml*) excise tax on carbonated soft drinks, energy drinks, and sweetened juice drinks (a product set that is roughly equivalent with our definition of SSBs) would lead to a long-run reduction in purchases of these beverages by 3.58*l* and 3.35*l* for low- and high-income households, respectively [48]. Valizadeh and Ng (2021) observed similar figures per quarter per capita for a one cent per ounce tax at the median quantile of SSB purchasing [45]. Our findings are also consistent with observed reductions in SSB consumption after the implementation of SSB taxes. A meta-analysis evaluating implemented SSB taxes found an average observed reduction of sales by 15% (95%-confidence interval [95%-CI]: 9%; 20%; N = 35) and a reduction in SSB consumption by 18% (95%-CI: -1%; 38%; N = 12) [41].

As suggested by economic theory we find that SSB taxation would lead to welfare losses among consumers which, in contrast to the effects on consumption, are concentrated among high-income households [28]. In fact, affluent households would increase their expenditure by €0.22 in the *Ad-Valorem Tax* scenario due to their inelastic demand for SSBs and would need to receive €1.33 to compensate for the welfare loss. The average CV for the *Ad-Valorem Tax* and the *Extended Ad-Valorem Tax* would be €0.78 and €1.52, respectively. High-income households would also incur the largest tax revenue at €1.53 and €2.81 per month for the respective scenarios. These findings are somewhat consistent with other studies that estimated welfare losses for SSB taxes [30,45,48].

We find that the tax would be regressive with respect to the share of the tax from monthly net income in both scenarios. Low-income households roughly pay twice the share compared to high-income households (*Ad-Valorem Tax*: 0.06% vs. 0.03%; *Extended Ad-Valorem Tax*: 0.11% vs. 0.05%). However, both simulated taxes would be progressive with regards to health because low- and middle-income households typically have a higher diet related NCD health burden and react stronger to increased SSB prices, thus reducing their consumption of SSBs by around 4*l* per month compared to around 1.5*l* for high-income households in our analysis [24]. Consequently, reductions in sugar consumption are larger among low- and middle-income households. The financial regressivity of a tax on SSBs may thus be justified, particularly when additionally considering potential internalities, and could in fact contribute to reducing income-related health inequalities [30,31]. Others have suggested that an unequal financial burden on the poor could further be mitigated by incorporating a compensation mechanism into financially regressive health taxes that ensures an indirect redistribution towards vulnerable populations via health promotion and community health programs [32]. However, in our context this remains a theoretical option since the earmarking of taxes is not allowed in Germany.

The findings from our study have important implications for the policy debate on health taxes in Germany. We show that households in Germany will likely show considerable reactions to increased prices of unhealthy beverages. However, our analysis of different tax designs, including those varying the tax rate based on sugar content as recommended by the WHO and the German SABAF, is limited by the aggregation level of the underlying data. Our results do also not support the concern that consumers will substitute towards untaxed sugary beverages. Yet, it is possible that reductions in SSB consumption will lead to long-run behavioral changes beyond beverage consumption patterns that mitigate some of the beneficial effects of reduced SSB sugar intake [29,81]. The international experience of SSB tax policy discussions and implementation evaluations shows that the introduction of such a policy may also have additional signaling effects towards consumers [82]. These signals pertain particularly to the perceived healthfulness of diets or specific foods which can, together with the support or opposition from industry and other stakeholders, affect social norms in the long run [83,84].

The present analysis has several important strengths. We conduct the first study to quantify demand parameters of non-alcoholic beverage sub-categories in Germany and stratify our analysis by household income providing key insights into demand heterogeneity. We are also the first to estimate welfare effects of SSB taxes in Germany. The used household expenditure survey has a large sample size, is generally of high quality and makes our results nationally representative. We apply established economic methods for demand estimation, controlling for censoring, quality effects, and seasonality. Additionally, in our analysis we employ robust controls of potential confounding factors. Finally, the results from our study allow researchers to quantify the potential long-term impacts of non-alcoholic beverage taxes across income groups.

The following limitations of our approach need to be considered. First, we were unable to differentiate between regular and diet SSBs due to the aggregation level in our data. Thus, potential substitution between these categories could not be estimated. Additionally, tap water is regularly consumed instead of packaged water in Germany but not collected in the ICS and thus not included in our analysis. Second, as we did not have access to product-level data, we could also not account for substitution between product of the same category with different levels of quality. However, we aimed to address this issue by adjusting unit values for quality effects. For the same reason we were also unable to analyze tax designs which vary the tax rate by sugar content. Third, cross-demand effects towards other foods were outside of the scope of this analysis but could be relevant for the long-term health effects of SSB taxes. Fourth, we did not differentiate demand parameters by beverage consumption level, sex, or age. Although evidence shows that there are heterogenous consumption patterns across these strata, we focused on household income in the stratified analysis. The primary reason was that our data is aggregated at the household-level making inferences about individual consumption, age, or sex difficult. Fifth, although we used data from two waves of the ICS (2013 and 2018) we did not account for inflation between those years. However, this does not impact our results because inflation levels were very low in and between the studied years. Finally, in the simulation of the tax scenarios we analyzed hypothetical price increases based on observed purchasing behavior which do not include potential signaling effects due to public discussions about tax introduction, changing social norms, or general behavioral adaption beyond price effects. Yet, without any implemented taxes, the implications of economic theory and their consequences for human behavior are an important tool to prospectively attempt to estimate the demand effects of SSB taxes.

Conclusion

We find that the demand for non-alcoholic sugary beverages in Germany is elastic, particularly among low- and middle-income households. Our simulations show that an SSB tax could meaningfully reduce consumption but would place a higher financial burden on low-income households. While the welfare effects related to taxation would be concentrated among high-income households, low- and middle-income households would react stronger to increased prices and thus accrue potentially higher health benefits. The introduction of tax on SSBs in Germany could reduce sugar consumption and reduce related health inequalities.

Tables

Table 1: Socio-demographic characteristics of household survey sample

	All Households (N = 21,636)		Low Income (N = 7,213)		Middle Income (N = 7,211)		High Income (N = 7,212)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Number of persons in household	2.12	1.10	1.91	1.09	2.27	1.17	2.19	0.99
Number of children:								
Age <1 year	0.01	0.09	0.01	0.09	0.01	0.10	0.01	0.09
Age 1 to 2 years	0.04	0.21	0.04	0.21	0.06	0.24	0.04	0.19
Age 3 to 5 years	0.06	0.27	0.06	0.27	0.07	0.29	0.06	0.25
Age 6 to 11 years	0.12	0.40	0.11	0.38	0.15	0.45	0.10	0.37
Age 12 to 17 years	0.12	0.41	0.12	0.40	0.15	0.44	0.11	0.38
Main earner occupation (%):								
Self-employed	0.05	0.22	0.05	0.22	0.05	0.21	0.06	0.23
Civil servant	0.08	0.28	0.01	0.12	0.07	0.26	0.16	0.37
White collar worker	0.41	0.49	0.28	0.45	0.45	0.50	0.49	0.50
Blue collar worker	0.08	0.27	0.09	0.29	0.10	0.30	0.05	0.21
Unemployed	0.04	0.19	0.10	0.30	0.01	0.09	0.00	0.06
Retired	0.30	0.46	0.36	0.48	0.31	0.46	0.24	0.42
Student	0.03	0.17	0.08	0.28	0.00	0.07	0.00	0.04
Other non-employed	0.01	0.09	0.02	0.14	0.00	0.06	0.00	0.05
Age of main earner (years)	53.07	16.18	52.26	17.88	53.53	16.24	53.42	14.18
Sex of main earner is male (%)	0.61	0.49	0.50	0.50	0.62	0.49	0.70	0.46
Number of employed household members	0.98	0.86	0.57	0.70	1.06	0.85	1.31	0.85
Nielsen region (%):								
Region I (HB, HH, NI, SH)	0.17	0.37	0.17	0.37	0.16	0.37	0.17	0.37
Region II (NRW)	0.18	0.38	0.17	0.37	0.17	0.38	0.20	0.40

Region IIIa (HE, RP, SL)	0.15	0.36	0.13	0.34	0.15	0.35	0.17	0.38
Region IIIb (BW)	0.11	0.31	0.09	0.29	0.11	0.32	0.13	0.34
Region IV (BY)	0.15	0.36	0.12	0.32	0.15	0.36	0.18	0.39
Region V/VI (BE, BB, MV, ST)	0.14	0.35	0.18	0.39	0.15	0.36	0.09	0.29
Region VII (SN, TH)	0.10	0.30	0.14	0.34	0.11	0.31	0.05	0.23
Net household income per month (€)	3,750	2,610	1,750	810	3,430	1,170	6,050	3,000
Total food and beverage expenditure per household per month (€)	255.83	150.16	199.53	122.79	266.72	145.91	301.26	161.02
Average temperature per month in federal state (°C)	9.80	7.00	9.75	7.06	9.77	7.05	9.88	6.90

Abbreviations: SD, Standard deviation.

Table 2: Quantities, prices, adjusted unit values, expenditure, and budget shares of non-alcoholic beverages among consuming households

	Flavored Milk		Plain Milk		Water		SSBs		Juice		Coffee & Tea	
Measure†	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD	Mean	RSD
	Quantities (consuming households)*											
All households	1.804	1.359	9.725	1.008	34.386	0.952	17.921	1.273	8.282	1.274	1,167.052	1.099
Low Income	1.810	1.436	8.954	1.083	30.370	1.016	17.405	1.296	7.354	1.198	1,028.781	1.091
Middle Income	1.873	1.342	10.407	0.999	35.645	0.927	19.260	1.260	8.851	1.325	1,204.897	1.088
High Income	1.720	1.278	9.777	0.943	36.788	0.917	17.040	1.254	8.557	1.251	1,261.927	1.096
	Unit value (€ per unit - unadjusted)*											
All households	2.236	0.781	0.806	0.334	0.393	1.136	0.997	0.878	1.481	0.825	0.016	1.646
Low Income	2.102	0.741	0.764	0.333	0.352	1.152	0.892	0.858	1.358	0.796	0.015	1.034
Middle Income	2.199	0.742	0.798	0.332	0.392	1.231	0.988	0.888	1.459	0.792	0.016	2.115
High Income	2.421	0.835	0.854	0.326	0.432	1.025	1.114	0.863	1.612	0.856	0.018	1.536
	Adjusted unit values (€ per unit - adjusted)*											
All households	2.020	0.135	0.786	0.087	0.290	0.101	0.985	0.115	1.497	0.098	0.017	0.107
Low Income	1.997	0.134	0.773	0.087	0.285	0.101	0.968	0.115	1.474	0.097	0.016	0.109
Middle Income	2.017	0.134	0.784	0.087	0.289	0.101	0.980	0.113	1.491	0.097	0.016	0.107
High Income	2.047	0.135	0.800	0.083	0.296	0.097	1.007	0.113	1.525	0.095	0.017	0.103
	Expenditure (€ per month)											
All households	3.218	1.287	7.538	1.017	11.009	1.124	12.787	1.204	9.795	1.189	13.136	1.065
Low Income	3.041	1.352	6.526	1.073	8.438	1.237	11.014	1.212	8.052	1.102	10.463	0.948
Middle Income	3.307	1.220	7.947	0.990	11.264	1.089	13.707	1.207	10.212	1.194	13.267	1.033
High Income	3.316	1.292	8.090	0.984	13.095	1.041	13.620	1.168	10.957	1.190	15.580	1.083
	Budget share (%)											
All households	0.081	1.313	0.213	0.872	0.270	0.778	0.276	0.794	0.230	0.787	0.341	0.660
Low Income	0.092	1.240	0.229	0.872	0.261	0.810	0.295	0.776	0.241	0.791	0.354	0.653
Middle Income	0.077	1.280	0.207	0.852	0.266	0.769	0.272	0.793	0.224	0.778	0.332	0.665
High Income	0.074	1.430	0.204	0.882	0.282	0.758	0.260	0.810	0.227	0.789	0.337	0.660

*litres per month, except coffee & tea in grams per month. The relative standard deviation (RSD) is defined as the standard deviation divided by the mean (this is alternatively often called "coefficient of variation" which we do not use to avoid confusion with "compensating variation"). †All reported measures only include households that purchased the respective beverage category. Purchasing probabilities were very similar across household income categories. See Appendix Table 11.

Table 3: Estimated own-, cross-price and expenditure elasticities of different non-alcoholic beverage categories for all households

Beverage category	Price elasticities						Expenditure elasticities
	Flavored milk	Plain milk	Water	SSBs	Juice	Coffee & Tea	
Uncompensated (Marshallian)							
Flavored milk	**-1.055*****	-0.036	-0.077	0.087	0.203	-0.073	0.951***
Plain milk	-0.018	**-0.788*****	-0.082	0.038	-0.063	0.006	0.907***
Water	-0.029	-0.067	**-0.801*****	-0.036	0.08	-0.072	0.925***
SSBs	0.026	0.012	-0.055	**-0.956*****	0.047	-0.104*	1.032***
Juice	0.077	-0.081	0.068	0.052	**-1.106*****	-0.063	1.053***
Coffee & Tea	-0.024	-0.024	-0.088*	-0.089*	-0.044	**-0.801*****	1.07***
Compensated (Hicksian)							
Flavored milk	**-1.043*****	0.135	0.126	0.251	**0.349***	0.182#	
Plain milk	-0.007	**-0.625*****	0.111	**0.195***	0.076	**0.25****	
Water	-0.017	0.1	**-0.604*****	0.124	**0.222****	**0.176****	
SSBs	0.039	**0.197****	**0.165***	**-0.778*****	**0.205***	**0.172*****	
Juice	0.09	0.108	**0.292****	**0.234***	**-0.944*****	**0.219*****	
Coffee & Tea	-0.011	**0.168*****	**0.14****	**0.096***	**0.121****	**-0.514*****	

Price elasticities by beverage category, where a 1% change in price of the category in column *j* leads to a change in consumption of the category in row *i* with the magnitude of the respective own- or cross price elasticity (expressed in %). Statistical significance: *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; # = $p < 0.10$.

Table 4: Estimated own-price and expenditure elasticities of different non-alcoholic beverage categories by household income

Beverage category	Subgroups: All Households	Income: Low	Income: Middle	Income: High
Uncompensated (Marshallian) own-price elasticities				
Flavored milk	-1.055***	-1.279***	-0.755**	-1.089***
Plain milk	-0.788***	-0.561#	-0.844**	-1.059***
Water	-0.801***	-0.654***	-1.032***	-0.719***
SSBs	-0.956***	-1.138***	-1.244***	-0.431*
Juice	-1.106***	-1.027***	-1.265***	-1.045***
Coffee & Tea	-0.801***	-0.947***	-0.815***	-0.743***
Compensated (Hicksian) own-price elasticities				
Flavored milk	-1.043***	-1.264***	-0.744**	-1.079***
Plain milk	-0.625***	-0.392	-0.688*	-0.889**
Water	-0.604***	-0.486*	-0.826***	-0.51**
SSBs	-0.778***	-0.948***	-1.054***	-0.269
Juice	-0.944***	-0.858**	-1.119***	-0.877***
Coffee & Tea	-0.514***	-0.667***	-0.523***	-0.461***
Expenditure elasticities				
Flavored milk	0.951***	1.033***	0.917***	0.929***
Plain milk	0.907***	0.902***	0.885***	0.968***
Water	0.925***	0.871***	0.956***	0.906***
SSBs	1.032***	1.036***	1.081***	1.017***
Juice	1.053***	1.119***	0.955***	1.067***
Coffee & Tea	1.07***	1.036***	1.093***	1.057***

Own-price/expenditure elasticities by beverage category, where a 1% change in price of the category leads to a change in consumption/expenditure of the same category with the magnitude of the respective own-price/expenditure elasticity (expressed in %). Statistical significance: *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; # = $p < 0.10$.

Table 5: Absolute and relative consumption variation for taxation scenarios by household income

Beverage categories	Absolute changes†		Relative changes in %†	
	Ad-Valorem Tax	*Extended Ad-valorem Tax*	*Ad-Valorem Tax*	*Extended Ad-valorem Tax*
Flavored milk*				
All Households	0.026	-0.295	1.435	-16.475
Low Income	0.081	-0.318	4.358	-17.898
Middle Income	0.056	-0.191	2.975	-10.193
High Income	-0.083	-0.37	-4.863	-21.774
Plain milk*				
All Households	0.051	-0.047	0.490	-0.442
Low Income	-0.03	-0.155	-0.311	-1.588
Middle Income	0.19	-0.108	1.682	-0.979
High Income	-0.029	0.009	-0.282	0.094
Water*				
All Households	-0.17	0.186	-0.478	0.533
Low Income	0.726	0.71	2.327	2.279
Middle Income	-0.101	1.206	-0.27	3.314
High Income	-1.087	-1.336	-2.843	-3.522
SSBs*				
All Households	-3.427	-3.281	-19.123	-18.342
Low Income	-3.963	-3.953	-22.769	-22.852
Middle Income	-4.791	-4.21	-24.878	-21.873
High Income	-1.47	-1.486	-8.625	-8.626
Juice*				
All Households	0.062	-1.743	0.704	-21.126
Low Income	-0.065	-1.541	-0.83	-20.976
Middle Income	0.327	-1.897	3.45	-21.703
High Income	0.026	-1.73	0.287	-20.254
Coffee & Tea*				
All Households	-13.145	-21.119	-1.103	-1.778
Low Income	-4.35	-0.2148	-0.416	-0.019
Middle Income	-12.275	-33.1	-1	-2.698
High Income	-26.755	-32.408	-2.072	-2.518

*litres per month, except coffee & tea in grams per month. †The own- and cross-price effects leading to the reported changes in the taxation scenarios are only meaningful for households that purchased the respective beverage category and are zero otherwise. See equation (8).

Table 6: Expenditure changes and welfare effects of taxation scenarios by household income

Welfare effects†	*Ad-Valorem Tax*		*Extended Ad-valorem Tax*	
	Mean	RSD	Mean	RSD
Change in household expenditures (€)				
All Households	-0.305	-1.571	-0.669	-1.13
Low Income	-0.426	-2.014	-0.709	-1.44
Middle Income	-0.609	-2.325	-0.964	-1.387
High Income	0.22	5.981	-0.242	-6.015
Compensating variation (€)				
All Households	0.78	1.221	1.516	1.211
Low Income	0.492	1.747	1.042	1.353
Middle Income	0.601	2.123	1.418	1.467
High Income	1.327	1.549	2.167	1.271
Tax revenue per household per month (€)				
All Households	1.296	1.706	2.426	1.257
Low Income	1.059	1.722	1.937	1.287
Middle Income	1.326	1.678	2.573	1.244
High Income	1.526	1.691	2.812	1.214
Tax share in monthly net income (%)				
All Households	0.042	2.064	0.079	1.565
Low Income	0.061	1.994	0.113	1.542
Middle Income	0.037	1.664	0.07	1.207
High Income	0.026	1.695	0.049	1.185

The relative standard deviation (RSD) is defined as the standard deviation divided by the mean (this is alternatively often called "coefficient of variation" which we do not use to avoid confusion with "compensating variation"). †The welfare effects resulting from the taxation scenarios are reported across all households because they result from the combination of all category purchase combinations and thus represent population means.

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B.2. The implications of policy modeling assumptions for the projected impact of sugar-sweetened beverage taxation on body weight and type 2 diabetes in Germany

Bibliographic information:

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Summary of methods and results:[‡¶]

The main objective of this study was to analyze how the projected impact of a 20% value-added[†] SSB tax on BMI is affected by different policy modeling assumptions. The secondary objectives were to assess the implications for related savings in healthcare costs attributable to T2DM and to compare the relative magnitude of the resulting uncertainty to different taxation scenario specifications.

In the baseline scenario we evaluated the impact of a 20% value-added tax on long-term BMI using a standard price elasticity approach and an established energy balance equation. We then assessed the impact of several literature-based modifications of modeling assumptions related to the policy, on the change in SSB consumption, energy intake, and consequently the predicted change in BMI under the tax. These included (1) the adjustment of the SSB own-price elasticity for baseline SSB consumption; (2) using an alternative SSB own-price elasticity from a meta-analysis of empirical studies; (3) adjusting baseline SSB intake for misreporting; (4) including substitution to fruit juice; (5) adjusting the cross-price elasticity between SSBs and fruit juice for SSB consumption; and (6) implementing substitution to fruit juice based on volume. In alternative scenarios, we varied the tax rate between 10-30% and considered the additional taxation of fruit juice. To further analyze the implications of these different assumptions, we subsequently modelled impacts on T2DM and related healthcare costs over the lifetime of the German adult population age 20 years and older with a simple MSLT cohort simulation model. Data sources for the used model input parameters included official demographic, epidemiological surveillance, and nationally representative dietary data from the NVS II[‖].

In the main analysis we found moderate reductions in long-term BMI under a 20% tax on SSBs which were largest among men age 20 to 24 years. This would lead to about 220,000 fewer cases of overweight and 290,000 fewer cases of obesity in Germany. Using the MSLT model we simulated that these reductions in BMI would avert 77,000 DALYs, prevent 2.3 million years lived with T2DM, and lead to healthcare cost savings of €2.4 billions over the lifetime of the population. However, the estimated policy impacts varied largely under different modeling assumptions. For example the number of DALYs averted ranged from -18,000 when including substitution to fruit juice to 164,000

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†This is equivalent to an *ad valorem* tax.

‡We explicitly do not provide references in this short summary and refer to the respective publication.

‖In contrast to the inputs for PRIMEtime, the inputs for this study were estimated before those for $\text{IMPACT}_{\text{NCD}}$ Germany. Both are thus not entirely consistent.

when adjusting baseline SSB consumption for misreporting. Importantly, this structural uncertainty was similar to the variability of mean policy impacts between scenarios with alternative tax rates.

With this study we were able to show how the projected policy impact of SSB taxation in simulation modeling studies might to some degree depend on assumptions about the implementation of the policy mechanism. Because these assumptions are made by researchers and can vary substantially between studies, the resulting uncertainty and their implications need to be reported transparently. Particularly, we argue that the heterogeneity in the behavioral response to public health policies should be better reflected in future modeling studies. This would lead to a better analysis of health inequalities and enable better policy comparisons and recommendations.

Title: The implications of policy modeling assumptions for the projected impact of sugar-sweetened beverage taxation on body weight and type 2 diabetes in Germany

Running head: Implications of modeling assumptions for body weight change

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Abstract

Background

The evaluation of sugar-sweetened beverage (SSB) taxation often relies on simulation models. We assess how assumptions about the response to SSB taxation affect the projected body weight change and subsequent health and economic impacts related to type 2 diabetes mellitus (T2DM) using Germany as an example.

Methods

In the main analysis, we estimated changes in energy intake by age and sex under a 20% value-added tax on SSBs in Germany using marginal price elasticities (PE) and applied an energy equilibrium model to predict body weight changes. We then quantified the impact of several assumption *modifications*: SSB own-PE adjusted for consumption (M1)/based on meta-analysis (M2); SSB consumption adjusted for underreporting (M3); substitution via marginal (M4a) or adjusted (M4b) cross-PE/as % of consumption change (M4c). We also assessed *scenarios* with alternative tax rates of 10% (S1) or 30% (S2) and including fruit juice (S3). We calculated overweight and obesity rates per *modification* and *scenario* and simulated the impact on T2DM, associated healthcare costs and disability-adjusted life years (DALYs) over the lifetime of the 2011 German adult population with a Markov model. Data included official demographics, national surveys, and meta-analyses.

Results

A 20% value-added tax in Germany could reduce the number of men and women with obesity by 210,800 [138,800; 294,100] and 80,800 [45,100; 123,300], respectively. Over the population lifetime this would lead to modest T2DM-related health and economic impacts (76,700 DALYs [42,500; 120,600] averted; €2.37 billion [1.33; 3.71] costs saved). Policy impacts varied highly across *modifications* (all in DALYs averted): (M1) 94,800 [51,500; 150,700]; (M2) 164,200 [99,500; 243,500]; (M3) 52,600 [22,500; 91,100]; (M4a) -18,110 [-111,500; 68,300]; (M4b) 25,820 [-31,430; 81,480]; (M4c) 33,810 [17,200; 56,510]. The variability in policy impact related to *modifications* was similar to the variability between alternative policy *scenarios* (all in DALYs averted): (S1) 26,400 [9,300; 47,600]; (S2) 126,200 [73,600; 194,500]; (S3) 342,200 [234,200; 430,400].

Conclusions

Predicted body weight reductions under SSB taxation are sensitive to assumptions by researchers, often needed due to data limitations. Because this variability propagates to estimates of health and economic impacts, the resulting structural uncertainty should be considered when using results in decision-making.

Keywords: Sugar-sweetened beverages; health taxation; simulation modeling; structural uncertainty; health policy; obesity; type 2 diabetes

1. Background

Consistent evidence shows that the consumption of sugar-sweetened beverages (SSBs) contributes to poor diets and the global health and economic burden of non-communicable diseases (NCDs) [1]. SSB consumption is directly and indirectly associated with morbidity and mortality through overweight and obesity, dental caries, cancer, osteoarthritis, cardiovascular disease, and type 2 diabetes mellitus (T2DM) [2-6].

To reduce this burden, the taxation of SSBs has been proposed for many years [7, 8]. Depending on their objective, SSB taxes are designed to reduce SSB and/or sugar consumption, incentivize reformulation and additionally generate revenue to compensate for negative externalities through the associated disease burden [7, 9, 10]. Over 45 countries and jurisdictions have implemented taxes on SSBs of different magnitude and design (e.g., tiered vs. flat tax) and the World Health Organization (WHO) recommends taxation of SSBs as an important preventive policy to achieve global NCD targets [11-13]. However, no such policy is currently enacted in Germany [13].

Simulation models have been widely used to estimate the expected long-term health and economic impact of SSB taxation policies [14]. These models combine the best available epidemiological and economic evidence in a mathematical model to simulate policy scenarios compared to a counterfactual 'do-nothing' scenario. Results from modeling studies can therefore guide policymakers and promote effective NCD prevention [14-16].

However, the outputs of such models are subject to different sources of uncertainty. These arise for example from statistical estimation procedures, analytical decisions and simplifying assumptions [17]. Additionally, researchers often face challenges in data availability and quality, which is of particular importance in nutrition-related applications due to measurement biases such as underreporting [14, 18, 19]. The latter partly relates to both parameter uncertainty (e.g., the variation in mean SSB consumption per age-sex group) and structural uncertainty (e.g., the assumption that mean SSB consumption is underreported and the decision to account for this). The quantitative implications resulting from these alternative assumptions may impact policy recommendations [20, 21].

Another aspect of structural uncertainty in this context is the approach used to estimate the population response to the modelled taxation policy. For fiscal policies targeting SSBs, this is the reduction in SSB and consequent reduction in sugar consumption following an increase in prices or reformulation. Because sugar is high in calories, net reduction in sugar consumption in theory leads to reduced overall caloric intake and eventually weight reduction [22]. Therefore, the link between the taxation policy and behavior change that results in SSB consumption change, including the compensatory consumption of other commodities (e.g., fruit juice), is key for validly projecting long-term health benefits [14].

Most applied modeling studies implement this behavioral response to SSB taxes with price elasticities of demand which quantify the change in SSB demand based on a change in price [14, 23]. However, a drawback of this approach is that researchers often assume the same marginal own- and cross-price elasticities for the whole population due to data limitations [14]. This disregard of behavioral heterogeneity may lead to an over- or underestimation of projected consumption changes. Economic studies based on high-dimensional consumer data have shown that this indeed is a critical assumption [24-26].

In this study we aim to assess how a range of policy modeling assumptions may affect the projected body weight reduction under a hypothetical 20% value-added tax on sugar-sweetened beverages in Germany. We do this by 1) testing modifications of own- and cross-price elasticities of SSBs and fruit juice which induce heterogeneity compared to standard price elasticities; and 2) comparing alternative approaches of implementing the effects of taxation in the model. We then use an established Markov cohort simulation model developed for the ACE-Obesity Policy study [27] and adapted to Germany to model the impact of the estimated weight reductions on T2DM and related healthcare costs. Lastly, we also explore different scenarios of tax rate and taxed beverage categories (SSBs-only vs. SSBs and fruit juice) to understand the relative importance of the structural uncertainty arising from the assessed policy modeling assumptions.

2. Methods

2.1. Study overview

Our approach to estimate the impact of SSB taxation comprised several conceptual steps, which are illustrated in **Figure 1**. First, we derived the relative change in SSB prices. Second, we calculated the resulting change in SSB consumption. Third, we estimated the long-term shift in the body weight (and consequently body mass index [BMI]) distribution resulting from changes in energy intake with established energy balance equations. Finally, we used a proportional multi-state life table Markov simulation model to analyze the resulting long-term health and economic impacts on type 2 diabetes compared to a 'do-nothing' scenario. We analyzed the structural uncertainty in the projected long-term BMI change and consequent T2DM-related impacts by investigating alternative modeling assumptions for estimating the change in SSB consumption including the consideration of caloric substitution (second step; hereafter: *modifications*). We additionally assessed alternative policy scenarios in which we varied the tax rate and considered the additional taxation of fruit juice (hereafter: *scenarios*).

Simulation modeling analyses were conducted over the lifetime (i.e., maximum age of 100 years) of the 2011 German population aged 20 years and older, stratified by sex and 5-year age cohorts. We chose 2011 as the base year of our analysis and simulation model because most required data inputs were available for this, or adjacent years and we could not identify newer data sources. Although we acknowledge that our result are not representative for the current German population, this is not relevant for the quality of our analysis as we are primarily interested in the variability of estimated policy impacts due to structural uncertainty arising from policy modeling assumptions. Data sources included German official demographic, disease surveillance and nationally representative dietary data. We provide an overview of input data and parameters in **Appendix 1**.

2.2. Main taxation scenario

As the main scenario, we considered a hypothetical 20% value-added tax on SSBs in Germany, which is described to be the minimum tax amount to substantially influence SSB purchasing and corresponds to the average rate of implemented taxes globally [28]. The tax was assumed to target SSBs which were defined as all soft and fruit drinks with added caloric sweeteners, but not fruit juice without added sweeteners or artificially sweetened beverages, which is consistent with many implemented taxes [13]. Based on recent findings, we assumed a tax pass-through from producers to consumers of 82% and that no relevant substitution to untaxed beverage categories would occur [11]. For simplicity, we assumed no substitution to fruit juice or milk in the main analysis and explore this in detail under different assumptions via the implemented *modifications*.

2.3. Impact of SSB taxation on SSB consumption

In order to estimate the change in beverage consumption based on a taxation policy two key input parameters are needed. First, the baseline level of consumption for all taxed beverage categories and potential substitutes is needed. Second, parameters indicating the demand for the relevant beverage categories based on changes in price (i.e., price elasticities) – here induced by the tax – are needed to estimate changes in consumption based on the baseline level.

2.3.1. Baseline beverage consumption

We used baseline data on BMI (in kg/m²), consumption of SSBs, fruit juice and milk (all in milliliters [ml] per day), and total energy intake (in kilocalories [kcal] per day) from the second *German National Nutrition Survey* (NVS II), which is the most contemporary population-based data source of dietary intake in Germany [29], aggregated by sex and 5-year age cohorts using the appropriate survey weights (**Appendix 1**). Although the NVS II was conducted between 2005 and 2007 it is appropriate for our purposes because we are not interested in population representativeness. Generally, per capita consumption of different non-alcoholic beverage categories in Germany has remained stable [30]. Information on SSB sub-categories (e.g., diet sodas) and the number of calories consumed per beverage category are not available in NVS II. We therefore assumed 48 kcal per 100 ml of SSB and 45 kcal per 100 ml of fruit juice based on a recent study from Canada, which estimated energy content based on sugar concentration in SSB sub-categories [31]. Considering the global scope of beverage production this assumption is reasonable. For the average caloric value of milk, we used 59 kcal per 100 ml, which is based on a German scientific report on the energy content of milk, weighted for different levels of fat, and adjusted for density [32, 33]. Separate information on flavored milk products was not available as these were included in the overall milk category of the NVS II.

2.3.2. Standard price elasticity approach

We calculated consumption per beverage category after the tax using data from an international meta-analysis, which, compared to more recent studies, included both own- and cross-price elasticities for SSBs and fruit juice [11, 34] (**Appendix 2**). Price elasticities measure the percentage change in demand of one good (e.g., SSBs) based on a 1% change in price of the same good (own-price elasticity) or another good (cross-price elasticity). For the own-price elasticity of SSBs we used a mean value of -1.299 and for the cross-price elasticities for SSBs to fruit juice and milk we used mean values of 0.388 and 0.129 [34]. As described above, we assumed no substitution between beverage categories in the main scenario, thus only considering the (average) own-price elasticity of SSBs.

2.3.3. *Modifications* of policy modeling assumptions

To assess structural uncertainty arising from modeling assumptions regarding the behavioral response to the SSB tax, we applied various literature-informed modifications. First, we investigated alternative assumptions that primarily affect the change in SSB consumption, including simplistic adjustments of own-price elasticities to assess the potential impact of heterogeneity by age as a proxy for consumption (*Modifications 1-3*). Second, we investigated several ways of implementing substitution to fruit juice and milk (*Modifications 4a-4c*).

2.3.3.1. *Modifications 1-3*: Assumptions affecting the change in SSB consumption

First, evidence shows that individuals with a high baseline consumption will react less elastic to the tax possibly due to mechanisms related to addiction (see for example Etilé & Sharma (2015)) [24, 25]. To account for this, we adjusted own-price elasticities of SSBs for the level of baseline SSB consumption in the respective age-sex cohort, taking advantage of the strong correlation between SSB consumption and age in the data (*Modification 1*). This adjustment resulted in lower elasticities for younger age groups (i.e., high SSB consumers) (**Appendix 6**). SSB own-price elasticities were adjusted with the following equation:

(1)
$$\delta_{\text{own},age} = \gamma \times \delta_{\text{own}} \times \frac{\overline{\theta_{sex}}}{\theta_{sex,age}}$$

where $\delta_{\text{own},age}$ is the adjusted age-specific own-price elasticity for SSBs, δ_{own} is the population level marginal own-price elasticity from [34], $\overline{\theta_{sex}}$ is the sex-specific mean consumption of SSBs, $\theta_{sex,age}$ is the age-sex-specific mean consumption of SSBs and γ is a scaling factor set to 0.5, which ensures that the mean of $\delta_{\text{own},age}$ for all males and females is equal to δ_{own}.

Second, we used an alternative estimate from a meta-analysis of interventional and prospective observational studies instead of analytically derived price elasticities (*Modification 2)*. Afshin et al. (2017) [35] estimated a decrease in SSB consumption of 6.74% for every 10% increase in SSB price, which resulted in a decrease of SSB consumption of 11.05% (for all age-sex cohorts) in our taxation scenario (pass-through of 82%).

Third, because predicted relative changes in SSB consumption directly depends on baseline SSB intake (see section *Standard price elasticity approach*), we adjusted SSB consumption for potential misreporting. We based this adjustment on the deviation of industry reported, export adjusted SSB consumption per capita from the self-reported consumption levels in the NVS II (*Modification 3*) [30]. As a result, we multiplied self-reported SSB consumption by 1.86 under the simplifying assumption that misreporting patterns and measurement biases were the same in all age-sex cohorts (**Appendix 6**).

2.3.3.2. Modifications 4a-c: Assumptions about substitution between beverage categories

Fourth, we considered substitution to fruit juice and milk via estimates of cross-price elasticities, which were extracted from the literature together with the own-price elasticities of SSBs (*Modification 4a*) [34].

Fifth, we adjusted the above cross-price elasticity of fruit juice following a previous study to reflect that SSB high-consumers might have a higher cross-price elasticity of fruit juice with respect to the price of SSBs (i.e., are more likely to substitute SSBs with fruit juice)

(*Modification 4b*) [36] (**Appendix 6**). To achieve this, the respective cross-price elasticity was adjusted with the following equation:

(2) $$\delta_{\text{cross},age} = \delta_{\text{cross}} \times \frac{\theta_{sex,age}}{\overline{\theta_{sex}}}$$

where $\delta_{\text{cross},age}$ is the adjusted age-specific cross-price elasticity for SSBs and fruit juice, δ_{cross} is the marginal cross-price elasticity, $\overline{\theta_{sex}}$ is the sex-specific mean consumption of SSBs and $\theta_{sex,age}$ is the age-sex-specific consumption of SSBs. The cross-price elasticity for milk was not adjusted.

Lastly, we applied an alternative approach to include substitution effects based on a previous study which assumed that 61% of the consumed SSB volume that is reduced as a response to the tax will be substituted with fruit juice (*Modification 4c*) [37].

2.3.4. Policy scenario analyses

To understand the relative importance of the assumptions underlying the above modifications with respect to the estimated body weight change, we additionally conducted three policy scenario analyses. First, we varied the tax level to 10% (*Scenario 1*) and 30% (*Scenario 2*), respectively. Second, we assumed that the tax would additionally apply to fruit juice, which is also high in free sugars and may have detrimental health effects on T2DM [38]. Due to a lack of data, we assumed the same average own-price elasticity as for SSBs (*Scenario 3*).

2.4. Long-term change in body weight after the tax

For each modification and scenario, using the baseline and calculated post-tax consumption levels, we computed the resulting change in energy intake in kcal by age group and sex. We then estimated the age-sex-specific long-term population-level changes in body weight with an energy balance equation, which postulates that at the population level, a 1% decrease in total energy intake will lead to an approximately 0.7% reduction in body weight at equilibrium [39]. Uncertainty in weight change was assessed using a Monte Carlo approach with 2,000 iterations implemented in R version 4.2.0 [40], which takes stochastic uncertainty in mean beverage intake, price-elasticities, and pass-through into account and is detailed in **Appendix 3**. Based on this predicted change in body weight we calculated absolute and relative changes in overweight and obesity assuming a log-normal distribution of BMI [41].

2.5. Long-term health economic impact

We modeled the long-term health impact of changes in population-level BMI on T2DM, associated disability-adjusted life years (DALYs) and healthcare costs using a proportional multi-state life table Markov (MSLT) cohort model [27, 42, 43]. In the model, potential impact fractions (PIF) are used to estimate the proportion of T2DM incidence attributable to overweight and obesity [41]. Details on this widely adopted modelling method are given in **Appendix 4** and elsewhere [44-46].

The MSLT model is implemented in Microsoft Excel. Uncertainty from model parameters (second-order uncertainty) was assessed using the Excel add-in software "Ersatz" and "EpiGearXL" with 2,000 Monte Carlo iterations by sampling from appropriate probability distributions of key parameters (**Appendix 5**) [17]. Uncertainty in outcomes are presented as 95%-uncertainty intervals [47, 48].

2.5.1. Impact on Type 2 Diabetes Mellitus

We obtained the most recent data on incidence and prevalence of T2DM by age and sex from an 2011 analysis of the German statutory health insurance and retrieved all-cause and T2DM mortality rates from the German Health Data Reporting System (*Gesundheitsberichterstattung des Bundes*, www.gbe-bund.de) (**Appendix 1**) [49]. We estimated disease parameters for which no information was available based on prevalence, incidence, and mortality rates with DISMOD II [50].

To calculate the PIF of the shift in the BMI exposure distribution on T2DM incidence, we used published relative risks for T2DM per BMI unit increase stratified by age (**Appendix 1**) [41, 51].

2.5.2. Disability-adjusted life years and healthcare costs

We calculated DALYs with a recently published disability weight for T2DM [52] and prevalent life years with disability per person (i.e., pYLD rate) from the Global Burden of Disease Study (GBD) [53] (**Appendix 1**). Estimates of the 2011 German population by age and sex were retrieved from the Human Mortality Database [54] (**Appendix 1**).

To calculate potential healthcare cost savings we multiplied the number of prevalent T2DM cases with German healthcare costs per T2DM case. Estimates of one-year per-capita healthcare costs for patients with and without T2DM were based on a recent study using data from the largest statutory health insurance in Germany [55] (**Appendix 1**). Cost values were deflated to 2011 levels using the official German price index for the health sector. Projected savings are net of an increase in healthcare costs from other diseases due to longer life expectancy. Healthcare costs and DALYs were discounted at a rate of 3% [56].

3. Results

3.1. Main analysis

In the main analysis, we observed moderate reductions in population body weight under a 20% value-added SSB tax in men and women compared to the base-case without a tax (**Figure 2, Figure 3**). Because SSB consumption is strongly associated with younger age and male sex and the response to the tax is proportional to consumption when using price elasticities, the largest long-term reduction in body weight of on average around 0.82kg [95%-uncertainty interval: 0.57; 1.10] was predicted to occur in the cohort of men aged 20-24. In comparison, women in the age group 75+ are predicted to achieve only reductions of on average around 0.03kg [0.00; 0.07] (**Figure 2**).

Overall, the tax would lead to a reduction in the proportion of German men that are overweight and obese by 0.47 [0.32; 0.65] and 0.68 [0.45; 0.95] percentage points, respectively. This translates to 146,500 [99,200; 200,900] fewer men being overweight and 210,800 [138,800; 294,100] fewer being obese (**Table 1**). For women the reduction would be 0.21 [0.13; 0.31] percentage points in overweight (69,300 [43,000; 100,300] fewer cases) and 0.25 [0.14; 0.38] percentage points in obesity (80,800 [45,100; 123,300] fewer cases) (**Table 1**).

Over the lifetime of the cohort, this reduction in body weight would translate into modest impacts on the epidemiology of T2DM in Germany. Overall, the simulation predicted around 86,400 [42,600; 141,100] fewer incident cases of T2DM and over 2.27 million [1.26; 3.56] fewer prevalent years lived with the disease. This would translate into over 76,700 averted DALYs [42,500; 120,600] and healthcare cost savings of around €2.37 billion [1.33; 3.71] for the German statutory health insurance (**Appendix 7**).

3.2. Impact of policy modeling assumptions

3.2.1. Assumptions affecting the change in SSB consumption

The first set of modifications that we analyzed was related to assumptions affecting the projected change in SSB consumption under the hypothetical SSB taxation scenario (*Modifications 1-3*; **Appendix 6**). These analyses revealed that alternative assumptions for own-price elasticities as well as the assumed baseline level of SSB consumption might have a significant impact on the predicted change in body weight in men (**Figure 2)** and women (**Figure 3**).

Adjusting own-price elasticities for the level of SSB consumption (*Modification 1*) drastically decreased projected reductions in overweight and obesity for men (31,900 [18,600; 47,700] and 151,600 [90,200; 225,300] fewer cases) and for women (22,300 [10,100; 37,200] and 57,800 [26,300; 95,500] fewer cases) (**Table 1**). Similarly, implementing the policy via a meta-analytic estimate of the effect of observed price increases on SSB consumption (*Modification 2*) led to smaller body weight reductions compared to the main analysis (**Figure 2, Figure 3**). However, correcting self-reported SSB consumption for potential underreporting (*Modification 3*) resulted in substantially higher body weight reductions and impacts on overweight and obesity for men (292,400 [200,500; 398,800] and 416,800 [286,200; 566,800] fewer cases respectively) and women (145,200 [96,100; 203,200] and 177,600 [112,400; 255,900] fewer cases for overweight and obesity respectively) (**Table 1**, **Figure 2**, **Figure 3**).

Consequently, **Figure 4** shows that these diverging predictions of body weight reduction implied large structural uncertainty in the projected health and economic impact regarding the prevention of T2DM. However, how these are propagated through the simulation model can be complex. For example, despite comparably little reduction of body weight, T2DM prevention effects in *Modification 1* are larger than in the main analysis due to prevention at higher ages being more beneficial (**Figure 4**, **Appendix 7**).

3.2.2. Assumptions about substitution between beverage categories

The second set of modifications that we analyzed was related to assumptions affecting the potential caloric substitution to other beverages (*Modifications 4a-c*; **Appendix 6**). Here, the estimated impact of the analyzed SSB tax on body weight was considerably reduced (**Figure 2**, **Figure 3**).

Using standard (i.e., unadjusted) cross-price elasticities (*Modification 4a*), the tax led to a slight reduction in overweight and obesity among men (94,900 [36,500; 158,800] and 88,900

[-37,600; 213,900] fewer cases) and even increases in obesity among women (32,500 [-68,500; 142,000] more cases) (**Table 1**). The latter is a result of "over-substitution" to juice in women above age 50 due to how price elasticities are applied in the standard approach. When adjusting cross-price elasticities (*Modification 4b*) this phenomenon was alleviated by reducing cross-price elasticities for low SSB consumers (change in obesity: 107,100 [-4,300; 219,600] fewer cases among men; 6,500 [-75,600; 92,000] more cases among women). Lastly, implementing substitution to fruit juice as a percentage of the volume of SSBs consumed (*Modification 4c*) resulted in an attenuated but relevant decrease of body weight and prevented cases of overweight and obesity compared to the main analysis (men: 62,400 [38,400; 92,800] fewer cases of overweight and 92,200 [54,300; 140,700] fewer cases of obesity; women: 30,700 [17,500; 47,800] and 36,200 [18,300; 59,300] fewer cases) (**Table 1**, **Figure 2**, **Figure 3**). Again, this variability of predicted body weight reductions with respect to how substitution is considered leads to high structural uncertainty in the simulated lifetime health and economic impact related to the prevention of T2DM (**Figure 4**, **Appendix 7**).

3.3. Policy scenario analyses

When comparing alternative policy scenarios, we found that the projected change in body weight was expectedly sensitive to the tax rate (**Figure 2**, **Figure 3**). In *Scenario 1*, reducing the tax rate to 10% led to a smaller reduction in cases of overweight and obesity for both men (63,100 [40,500; 89,300] and 87,400 [51,200; 129,500] fewer cases) and women (26,100 [13,400; 41,200] and 26,200 [8,700; 47,200] fewer cases) (**Table 1**). Conversely, increasing the tax rate to 30% in *Scenario 2* resulted in almost twice the amount of cases of overweight and obesity prevented in both men (232,200 [159,300; 317,100] and 331,900 [225,200; 455,000] fewer cases) and women (112,600 [72,700; 159,600] and 134,900 [81,500; 198,600] fewer cases) (**Table 1**). The additional taxation of fruit juice in *Scenario 3* resulted in the largest weight reduction among policy scenarios across all age-sex cohorts and the biggest reduction in overweight and obesity (**Table 1**, **Figure 2**, **Figure 3**). The projected lifetime health and economic impacts in terms of DALYs and healthcare cost savings due to the corresponding prevention of T2DM were consistent with these findings (**Figure 4**, **Appendix 7**).

4. Discussion

4.1. Summary

In this study we assessed how projected changes in body weight due to the introduction of a hypothetical 20% added-value tax on SSBs in Germany might be affected by structural uncertainty related to policy modeling assumptions. Additionally, we used a cohort simulation model to estimate the resulting heterogeneity in the health and economic impact related to the subsequent prevention of T2DM.

In the main analysis, we projected that such a tax could lead to long-term reductions in population body weight, which were highest among the youngest age groups, particularly men, due to their high SSB consumption. Reductions in body weight ranged from 0.82kg in men aged 20-24 to only 0.03kg in women above the age of 75. Overall, the modelled tax was associated with ~220,000 fewer cases of overweight and ~290,000 fewer cases of obesity. It would additionally prevent 2.27 million years lived with T2DM, avert 76,700 related DALYs and save €2.37 billion in T2DM healthcare costs over the lifetime of the 2011 German population.

However, we showed that the predicted change in body weight and all subsequent outcomes such as changes in obesity prevalence and impacts on T2DM are highly variable with regards to the modeling assumptions made on how the SSB tax impacts behavior. We find that the variability in the prevented health burden under these assumptions is similar to the variability between alternative policy scenarios with different tax rates or taxed beverage categories. In particular, correctly specifying the baseline level of SSB consumption; whether assumed reductions in consumption are directly proportional to this baseline consumption level; and how potential mechanisms of caloric substitution are considered, can have meaningful impacts on predicted changes in body weight and subsequently simulated health and economic outcomes.

4.2. Comparison with other studies

In recent years, many studies have used simulation models to assess the health and economic impact of various diet policies, including the taxation of SSBs [14]. However, to our knowledge, this is the first study to comprehensively investigate how a range of common assumptions which researchers make about the behavioral impact of these policies influences the findings from simulation studies.

In Germany, others have assessed the impact of SSB taxation on caries, overweight and obesity alone, or linked a hypothetical price increase of so-called "sin goods" (i.e., tobacco, red meat and SSBs) by 50% to changes in the German Diabetes Risk Score to predict T2DM prevalence in 2040 [36, 57, 58]. These studies have also identified benefits of SSB taxation, although results are not directly comparable due to differences in modeling assumptions and disease pathways. Our results are further in line with international modeling studies on SSB taxation although direct quantitative comparisons are complicated by differences in policy scenarios, simulation techniques, populations, and time horizons [12, 45, 59, 60].

4.3. Implications of policy modeling assumptions

We add to the literature on the simulation of SSB taxes by explicitly identifying, explaining, and assessing possible analytical decisions related to the implementation of the policy mechanism in models (i.e., price increase leading to change in energy intake) in the presence of uncertainty regarding the “true” impact of the policy on consumption. Economic studies using food purchasing data from consumer panels show that there may be considerable heterogeneity in the response to taxes on goods, which are detrimental to health [24, 26, 61-63]. Here, habit formation, addiction, health literacy and psychological effects such as scarcity might affect changes in individual dietary behavior [64-66]. However, this complexity poses challenges to policy evaluation and is neither completely understood, nor reflected in public health economic modeling studies of taxes on unhealthy foods and beverages [67]. Although we only perform simple adjustments to marginal price elasticities based on baseline SSB consumption levels (*Modification 1*), which are grounded in theory and findings from economic studies, we show that assumptions about this aspect of heterogeneity can have important implications for projected long-term health and economic outcomes and can be of a similar magnitude as design aspects of the simulated policy, such as the tax rate.

One issue of particular relevance for taxes that target specific foods (e.g., SSBs) is the possibility of consumers substituting with other untaxed foods within (e.g., fruit juice) or outside the respective category (e.g., sweets) [68, 69]. We show that the crude application of cross-price elasticities can lead to unrealistic results in some circumstances (Modifications 4a-c). We found that in cohorts with a low SSB and high fruit juice consumption (i.e., women in higher age groups) over-substitution from SSBs to fruit juice and consequently weight gain occurs due to relative changes in consumption [36]. To better predict the impact of taxation policies on population health, price elasticities disaggregated by sociodemographic characteristics, dietary habits and weight status are required.

Although recent studies have concluded that there is no evidence for strong substitution to other beverage categories after the introduction of an SSB tax [11], some substitution of calories through various other food groups is likely to occur [69]. By comparing different assumptions regarding substitution in our simulation model we show that failure to account for these effects can, in some cases drastically, overestimate, but not fully eliminate, the potential projected public health benefits of SSB taxes. Additionally, we show that potential caloric substitutes of

SSBs should be considered in SSB taxation design to maximize impact. The correct specification of the response to price changes may also have important implications for other considerations relevant to the decision of policymakers for or against health taxes such as the projected tax revenue.

We further show that the influence of limitations in dietary intake data from population surveys, which is typically used in the simulation of dietary policies can be substantial. Because data collection in nutritional epidemiology is particularly prone to misreporting biases, modeling that relies on such data may be biased as well [14]. Particularly in the case of sin goods, such as SSBs, underreporting can thus lead to an underestimation of the potential impact of policies.

4.4. Strengths and Limitations

Our study has several strengths. This is the first study to rigorously assess how different assumptions on the behavioral effect of SSB taxation can influence predicted body weight reductions. For this we compare common policy modeling assumptions with simple modifications guided by theoretical considerations and seminal studies. Further, to assess implications of the estimated long-term health and economic impact of SSB taxation on T2DM in Germany, we use an established simulation modeling framework, which has been used in various scenario modeling studies to evaluate diet policies.

This study has several limitations. First, while we consider heterogeneity in the policy response due to consumption levels, we are not able to account for other factors such as income which is associated with SSB consumption [1]. Second, we needed to rely on dietary intake and anthropometric data which was collected between 2005 and 2007, as well as on T2DM epidemiological data for 2011. However, aggregate data suggests that the consumption of non-alcoholic beverage categories has stayed roughly constant over the last decade [30]. Additionally, our main conclusion regarding the structural uncertainty arising from policy modeling assumptions is not affected by the timeliness or representativeness of the data. Third, our simulation approach only covers BMI as a risk factor and T2DM as an outcome, which ignores cancers and other cardiometabolic outcomes such as coronary heart disease. However, we explicitly do not aim to comprehensively simulate the health impact of SSB taxation scenarios in Germany but rather use this simple model to show the variability in simulation results that can be expected depending on assumptions about the policy mechanism. Fourth, the model assumes full effectiveness of the tax already in the first year of implementation and constant effectiveness in subsequent years, which likely leads to an overestimation of policy impact. Fifth, we do not include quality of life related to BMI or cost categories beyond healthcare costs in our modeling thus underestimating DALYs and economic impacts from lost productivity, tax revenue, as well as administrative and legislative costs arising when introducing a taxation policy. Finally, we do not incorporate uncertainty from several sources such as T2DM epidemiology, all-cause mortality, and future trends in BMI. However, as described above we use a simple model to draw out implications of structural uncertainty related to assumptions about the policy mechanism.

5. Conclusions

Our study illustrates that predicted body weight reductions under SSB taxation are sensitive to assumptions made by researchers. Because this variability propagates to the simulated health and economic impact, for which BMI often is the key risk factor, the resulting structural uncertainty should be taken into consideration in simulation studies. As policies to reduce the obesity burden are urgently needed despite imperfect information, rigorous simulation studies can provide decision makers with the range of possible outcomes under different policy scenarios. For future studies, data collection and the evidence underlying the behavioral response to health policies should be strengthened to reduce uncertainty concerning the long-term benefits of population-based preventive policies such as SSB taxes. The results from this study can thus serve as a reference for the structural uncertainty of SSB taxation impacts in evaluations that do not explicitly incorporate the implications of the assessed policy modeling assumptions.

List of abbreviations

BMI – Body mass index

DALY – Disability-adjusted life year

MSLT – Proportional multi-state life table Markov model

NCDs – Non-communicable diseases

NVS II – Nationale Verzehrsstudie II (German National Nutrition Survey II)

pYLD – Prevalent life years with disability

SSB – Sugar-sweetened beverages

T2DM – Type 2 diabetes

WHO – World Health Organization

Declarations

Ethics approval and consent to participate

This study did not require separate ethics approval or consent of participation because it used secondary data from the second German National Nutrition Study (*Nationale Verzehrstudie II*, NVS II) which was collected and is provided by the Max Rubner-Institute (MRI), Karlsruhe, Germany. We acknowledge that ethics approval and consent to participate from all individuals who participated in the NVS II was granted to the MRI.

Consent for publication

Not applicable.

Availability of data and material

The data underlying this article was collected during the second German National Nutrition Study (*Nationale Verzehrstudie II*, NVS II) by the Max Rubner-Institute (MRI), Karlsruhe, Germany and was requested by the study authors for use in this article. The NVS II data can be requested for scientific purposes after application to the MRI under https://www.mri.bund.de/de/institute/ernaehrungsverhalten/forschungsprojekte/nvsii/scientific-use-file/. The R code for input data preparation and the Excel sheet for the main model will be shared on reasonable request to the corresponding author.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

AF, KEF, MS, JA, and ML conceptualized and revised the design of the study. AF and KEF prepared the data and conducted the analysis. AF, KEF, MS, JA, and ML interpreted that data. AF and KEF prepared the initial manuscript draft. MS, JA, and ML authors reviewed, critically revised, edited the manuscript. All authors read and approved the final manuscript.

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6. Tables

Table 1: Reduction in overweight and obesity in Germany based on SSB taxation scenarios and assumption modifications

Main analysis	**%-point** reduction in proportion of overweight (95%-UI)	**%-point** reduction in proportion of obese (95%-UI)	Reduction in cases of overweight (95%-UI)	Reduction in cases of obese (95%-UI)
Men	0.47 (0.32; 0.65)	0.68 (0.45; 0.95)	146500 (99200; 200900)	210800 (138800; 294100)
Women	0.21 (0.13; 0.31)	0.25 (0.14; 0.38)	69300 (43000; 100300)	80800 (45100; 123300)
Scenarios				
Scenario 1				
Men	0.20 (0.13; 0.29)	0.28 (0.17; 0.42)	63100 (40500; 89300)	87400 (51200; 129500)
Women	0.08 (0.04; 0.13)	0.08 (0.03; 0.15)	26100 (13400; 41200)	26200 (8700; 47200)
Scenario 2				
Men	0.75 (0.51; 1.02)	1.07 (0.72; 1.46)	232200 (159300; 317100)	331900 (225200; 455000)
Women	0.35 (0.22; 0.49)	0.42 (0.25; 0.61)	112600 (72700; 159600)	134900 (81500; 198600)
Scenario 3				
Men	0.97 (0.71; 1.26)	1.74 (1.29; 2.21)	302000 (220700; 391500)	539400 (401700; 686400)
Women	0.78 (0.58; 1.01)	1.21 (0.9; 1.55)	253100 (187200; 327500)	392100 (290700; 503300)
Modifications				
Modification 1				
Men	0.10 (0.06; 0.15)	0.49 (0.29; 0.73)	31900 (18600; 47700)	151600 (90200; 225300)
Women	0.07 (0.03; 0.12)	0.18 (0.08; 0.29)	22300 (10100; 37200)	57800 (26300; 95500)

Main analysis	**%-point** reduction in proportion of overweight (95%-UI)	**%-point** reduction in proportion of obese (95%-UI)	Reduction in cases of overweight (95%-UI)	Reduction in cases of obese (95%-UI)
Modification 2				
Men	0.28 (0.12; 0.45)	0.42 (0.19; 0.69)	85600 (38700; 140000)	131100 (59600; 214500)
Women	0.14 (0.06; 0.23)	0.18 (0.08; 0.30)	45100 (20100; 74800)	57500 (25600; 97100)
Modification 3				
Men	0.94 (0.65; 1.28)	1.34 (0.92; 1.82)	292400 (200500; 398800)	416800 (286200; 566800)
Women	0.45 (0.30; 0.63)	0.55 (0.35; 0.79)	145200 (96100; 203200)	177600 (112400; 255900)
Modification 4a				
Men	0.31 (0.12; 0.51)	0.29 (-0.12; 0.69)	94900 (36500; 158800)	88900 (-37600; 213900)
Women	0.02 (-0.16; 0.20)	-0.10 (-0.44; 0.21)	7100 (-52000; 64900)	-32500 (-142000; 68500)
Modification 4b				
Men	0.23 (-0.02; 0.48)	0.34 (-0.01; 0.71)	70600 (-6400; 150600)	107100 (-4300; 219600)
Women	-0.02 (-0.23; 0.19)	-0.02 (-0.28; 0.23)	-5000 (-76100; 63000)	-6500 (-92000; 75600)
Modification 4c				
Men	0.20 (0.12; 0.30)	0.30 (0.18; 0.45)	62400 (38400; 92800)	92200 (54300; 140700)
Women	0.09 (0.05; 0.15)	0.11 (0.06; 0.18)	30700 (17500; 47800)	36200 (18300; 59300)

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7. Figures

Figure 1: Logic model of the sugar-sweetened beverage tax simulation modeling approach.

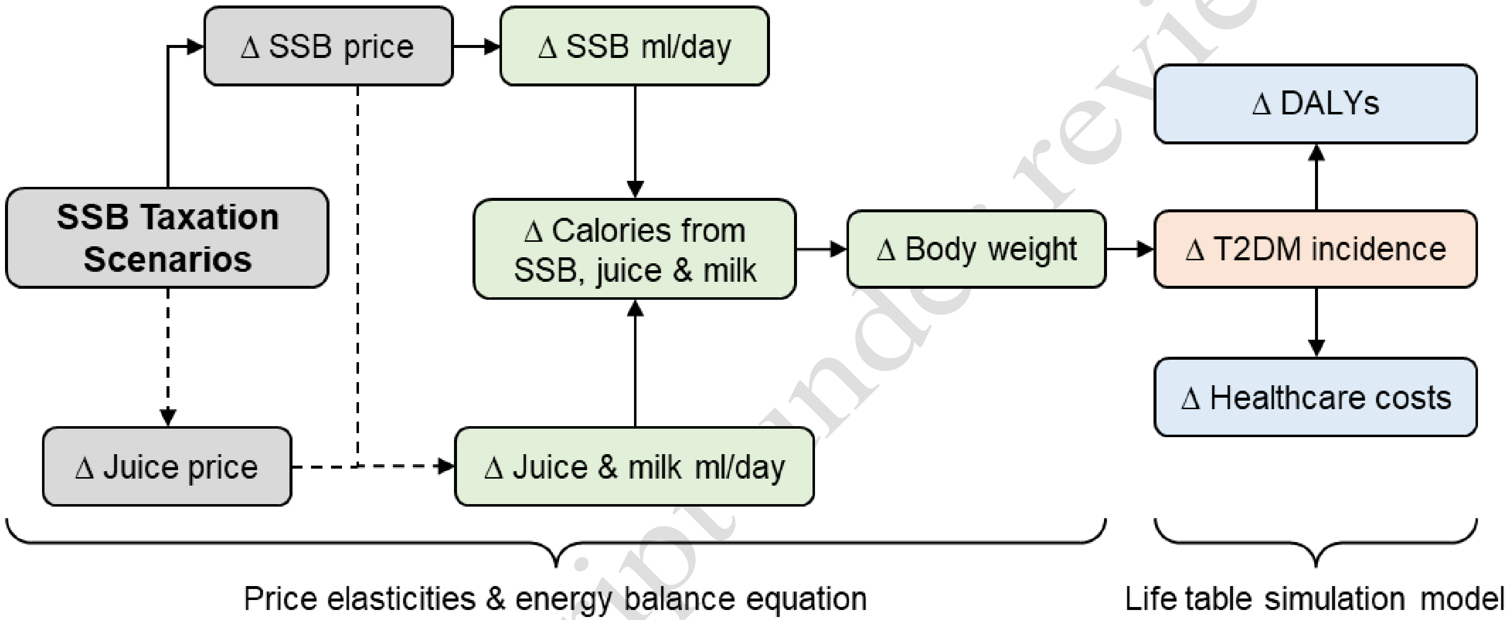

Figure legend: Logic model of the simulation approach depicting the conceptual pathways of the analyses. Solid arrows indicate pathways of the main analysis. Dashed arrows indicate pathways that are relevant for scenario and modification analyses, such as substitution and additional taxation of fruit juice. Abbreviations: DALY, disability-adjusted life years; ml, milliliter; SSB, sugar-sweetened beverages.

580 **Figure 2: Body weight change based on different SSB tax scenarios and assumption modifications by age group for men.**

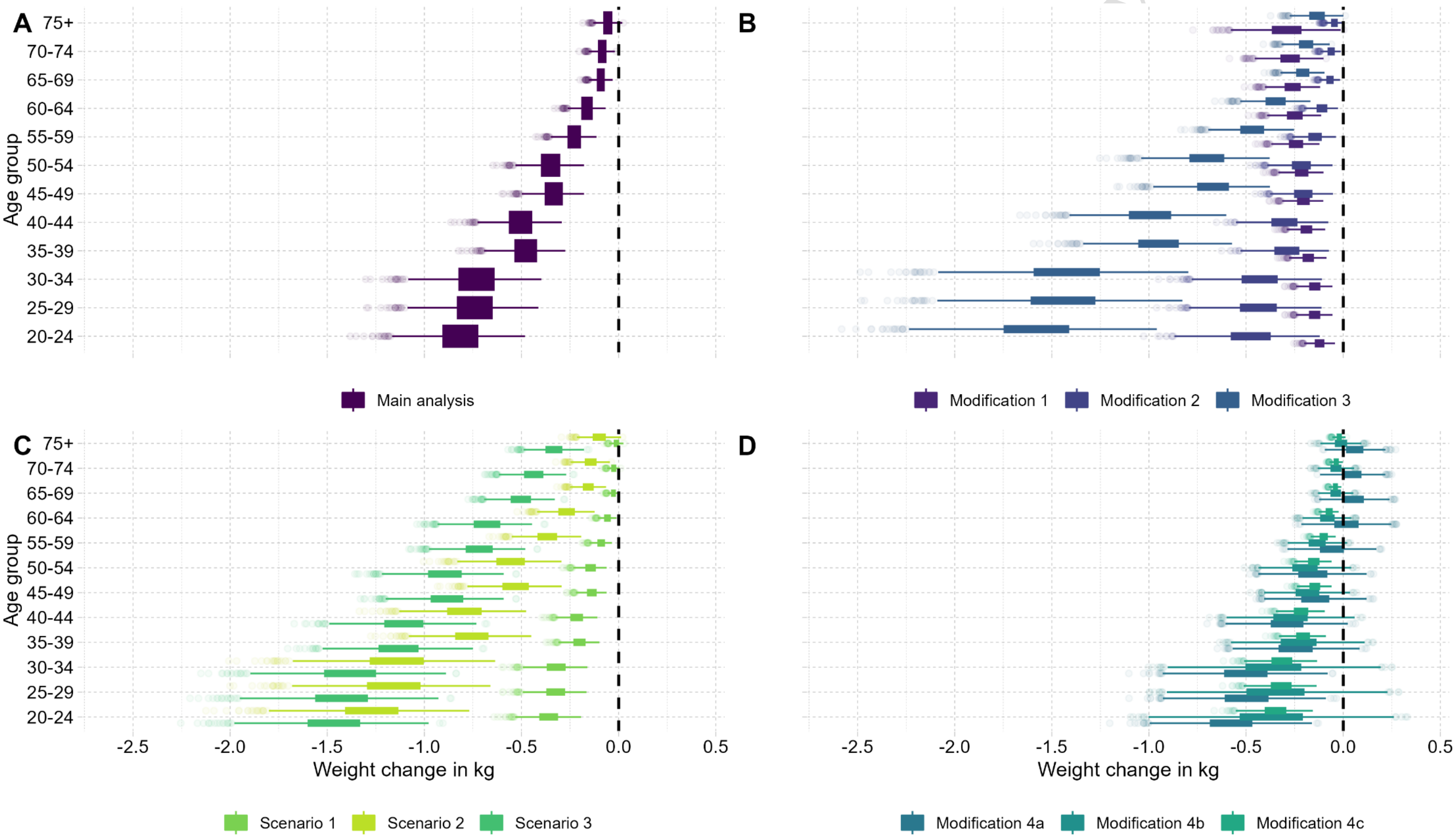

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Figure legend: Box plots display uncertainty in predicted body weight change based on 2,000 Monte Carlo simulations. The Monte Carlo sampling is based on the sample mean and standard error per beverage category from NVS II. The predicted change in energy intake using price elasticities and the corresponding long-term change in body weight based on Swinburn et al. (2009) is calculated per sample. Abbreviations: kg, kilogram.

586 **Figure 3: Body weight change based on different SSB tax scenarios and assumption modifications by age group for women.**

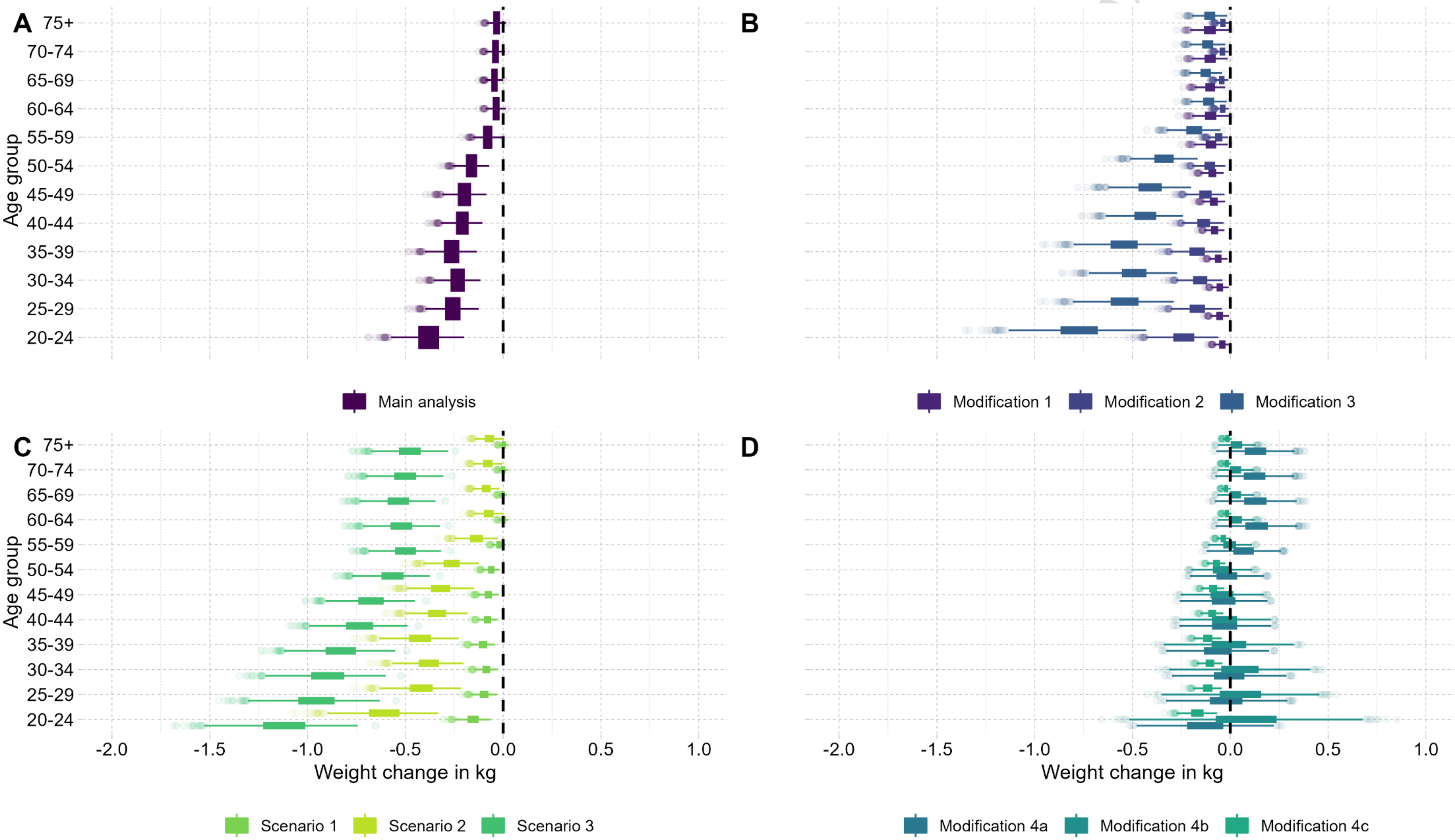

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Figure legend: Box plots display uncertainty in predicted body weight change based on 2,000 Monte Carlo simulations. The Monte Carlo sampling is based on the sample mean and standard error per beverage category from NVS II. The predicted change in energy intake using price elasticities and the corresponding long-term change in body weight based on Swinburn et al. (2009) is calculated per sample. Abbreviations: kg, kilogram.

Figure 4: Healthcare costs saved under SSB tax in structural uncertainty analyses as ratio to results of main analysis.

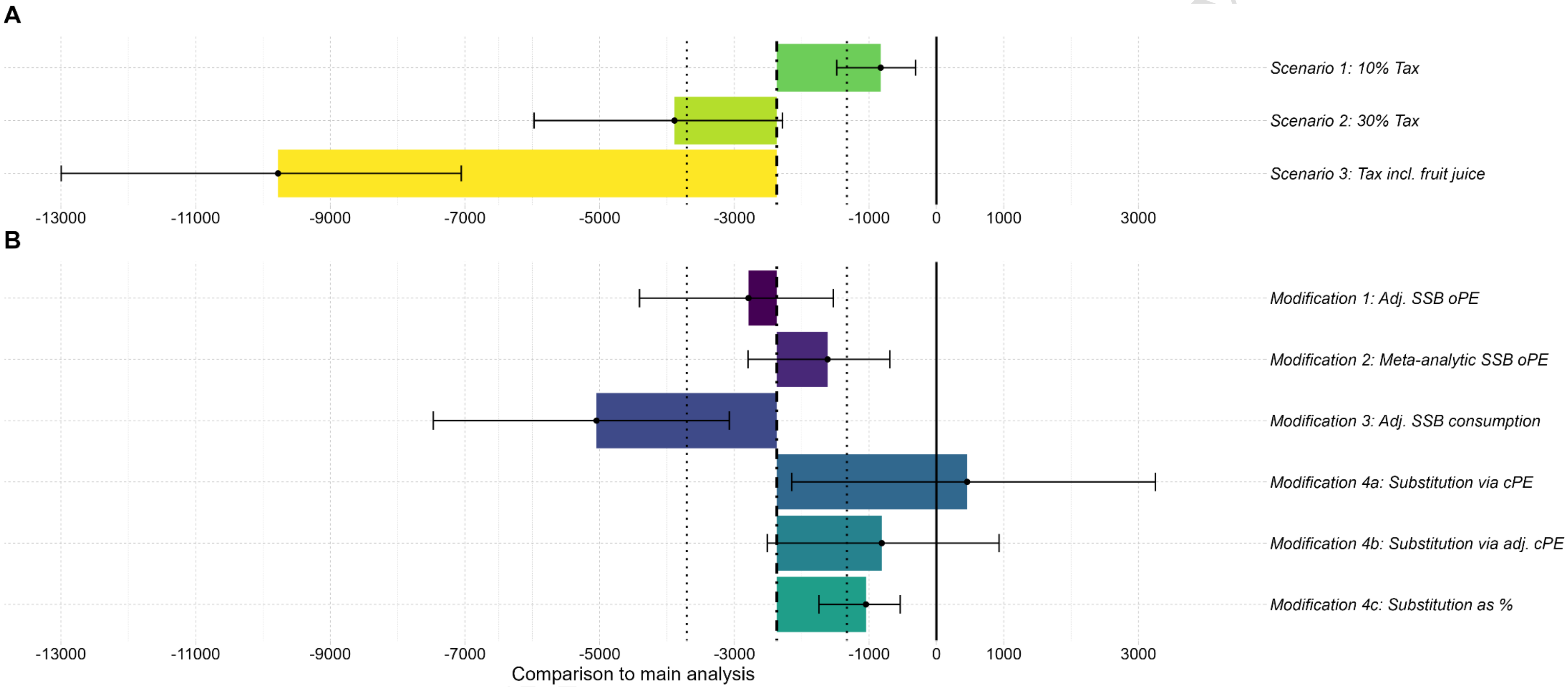

Figure legend: Panel A – Results from policy scenario analyses. Panel B – Results from structural uncertainty analyses. Plot shows the results of scenario and structural uncertainty analyses (colored bars = mean estimates; error bars = 95%-uncertainty intervals) in comparison to mean healthcare costs saved in main analysis (vertical dot-dashed line = mean estimate; vertical dotted lines = 95%-uncertainty interval).

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C. List of peer-reviewed publications

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D. List of conference contributions and presentations

1. 25. Jahrestagung des EBM-Netzwerks, 2024 in Berlin, Germany. Symposium: *Ansätze zur Evidenzgenerierung von Public-Health-Maßnahmen: Eine Einführung in quasi-experimentelle Methoden und deren Synergien mit Simulationsmodellen anhand einer Fallstudie zur Besteuerung von Zuckergetränken in Deutschland*.

2. RIGorous inference in Obesity Research (RIGOR) Award Lecture in the course Strengthening Causal Inference in Behavioral Obesity Research of the Indiana University School of Public Health-Bloomington, 2023 (virtual course). Presentation: *Estimating the Impact of Nutrition and Physical Activity Policies with Quasi-Experimental Methods and Simulation Modelling – Methods, Challenges and Synergies*. **Award endowed with US-$2,500**.

3. 15th European Public Health Conference (EUPHA), 2022 in Berlin, Germany. Oral presentation: *Impact of Sugar-Sweetened Beverage Taxation Scenarios in Germany: A Comparative Modelling Study*.

4. Seminar meeting of the Diet, Data, and Interventions Group at the Nuffield Department of Population Health, University of Oxford, 2022 in Oxford, United Kingdom. Presentation: *Modelling the Cost-Effectiveness of Diet Policies in Germany*.

5. Forum seminar of the Department of Public Health, Policy & Systems, University of Liverpool, 2022 in Liverpool, United Kingdom. Presentation: *The Health and Economic Impact of Sugar-Sweetened Beverage Taxation in Germany*.

6. Conference of the European Health Economics Association (EuHEA), 2022 in Oslo, Norway. Oral presentation: *Health and Economic Implications of Sugar-Sweetened Beverage Taxation in Germany: A Modelling Study*.

7. Society for Social Medicine & Population Health 65th Annual Scientific Meeting, 2021 (virtual conference). Oral presentation: *Projecting the Burden of Cardiovascular Disease and Diabetes in Germany: National Trends and Regional Inequalities*.

8. Policy Evaluation Network workshop on "Approaches to the evaluation of nutrition policies: state of the art, challenges and new directions", 2021 (virtual meeting). Presentation: *Simulation Modeling for the Economic Evaluation of Population-Based Dietary Policies: Insights from a Systematic Scoping Review*.

9. Policy Evaluation Network Work Package 3 seminar series, 2020 (virtual meeting). Presentation: *An Introduction to Simulation Modeling for Public Health and Food Policy Evaluation*.

10. 16th Symposium of the International Diabetes Epidemiology Group (IDEG), 2019 in Seoul, South Korea. Mini-oral Presentation: *Cost-effectiveness of a Collaborative Care Intervention for Diabetes Co-morbid Depression in India: Analysis of the Integrating Depression and Diabetes Treatment (INDEPENDENT) Trial*. **Award for 2nd best mini-oral presentation**.

E. List of supervised theses

1. P Da Costa e Silva. The impact of welfare reform on health: Summarizing the evidence from Germany. 2024. Bachelor's thesis for the TUM Health Science program.
2. J Eichinger. The impact of interventions addressing risk factors of colorectal and pancreatic cancer in Germany: A simulation modelling study. 2024. Master's thesis for the TUM Health Science program.
3. M Hassan. Sugar-sweetened beverage taxation in the United Kingdom and Ireland: A mixed methods analysis. 2024. Master's thesis for the TUM Health Science program.
4. J Bamberger. A narrative review of approaches to predict long-term changes in body weight or body mass index. 2023. Bachelor's thesis for the TUM Health Science program.
5. H Low. Comparing the Ukrainian and German health care systems: Insights for German migration policy and healthcare providers. 2023. Master's thesis for the TUM Health Science program.
6. ST Seneviratne. Risk of gestational diabetes mellitus among migrant women residing in high-income countries: A systematic review update and meta-analysis. 2022. Master's thesis for the TUM Health Science program.
7. A Veldhouse. Individual agency in community- and population-based depression prevention interventions and relationships to equity: A scoping review. 2022. Master's thesis for the TUM Health Science program.
8. D Marsing. Simulation modeling for the economic evaluation of obesity prevention policies in children and adolescents: a scoping review. 2022. Master's thesis for the LMU Public Health program.
9. A Felea. Health and economic implications of sugar-sweetened beverage taxation in Germany: A modelling study. 2020. Master's thesis for the TUM Life Science, Economics, and Policy program.
10. Y Zhao. An umbrella review of the cost-effectiveness of dietary- and physical activity- related interventions in the primary prevention of cardiometabolic diseases. 2019. Master's thesis for the LMU Public Health program.

F. Original dissertation proposal

Evaluation of policies addressing nutritional and physical activity behavior in Europe: Modelling approaches to assess the long-term cost-effectiveness of system-level policies†

Background: Non-communicable diseases are responsible for 73% of mortality and 60% of DALYs globally [1, 2]. Especially diabetes, obesity and cardiovascular disease (CVD), which are in close physiological interaction and have multi-faceted causal links, are responsible for almost half of this mortality [1-6]. These cardiometabolic diseases place an increasing burden on healthcare systems and societies through direct and indirect costs [7-13]. According to OECD data 13.9 – 20.1% of European health care expenditures are used to treat endocrine, nutritional, metabolic and circulatory diseases [14]. The main distal risk factors modifiable through system-level structural prevention policies addressing these diseases and their proximal risk factors are unhealthy diet and insufficient physical activity (PA) [15]. Across Europe a variety of policy measures with different approaches (i.e. market environment vs. informed choice) on multiple levels (i.e. school-based vs. countrywide) like public information campaigns, fiscal measures and nutrition-related standards have been implemented to address these distal risk factors [16-18]. Several European Union (EU) and World Health Organization (WHO) initiatives have focused on preventive policy regarding diet and PA in the past and provide an overview of the evidence while also explicitly pointing out gaps, prerequisites and challenges in adequate economic evaluation of these policies [17, 19, 20]. Yet, the EU lacks a consistent and valid framework for health policy evaluation although there is a high need. Mathematical simulation models can provide the needed complexity and time horizon for modelling the long-term health and economic effects of system-level structural preventive measures for diet and PA. Valid estimates are highly policy relevant and a crucial factor for efficient translation and decision making.

Research contribution: This dissertation will provide an important contribution to establishing an approach of health policy evaluation within the European Union which is a main goal of the JPI HDHL-PEN. The focus will be on the adequate decision analytic modeling of the long-term direct health economic effects of interventions addressing diet and/or PA in the EU. Hereby the following key points will be implemented:

- Initially a mapping review of the current literature on the health economic modelling of policies in diet and/or PA will be performed. This includes several important steps: Firstly, models that have been applied to policies in diet and/or PA will be identified. Secondly, previously applied model-policy combinations will be systematically mapped. Thirdly, model types, structures, mechanisms, assumptions, limitations and adaptability of each model will be critically appraised considering the modelled policies. Finally, outcomes within policy types, (cross-)validation issues and data requirements will be discussed including their application in the German and European context. This first part will result in a publication giving a comprehensive overview and mapping of the available evidence and methodology for economic policy evaluation in diet and/or PA.

- Based on the review process described above two or more models will be chosen and possibly adapted, cross-validated and compared within a single policy. This includes parameterization based on available evidence and self-conducted secondary analyses. This second part will apply the synthesized evidence from the review process and serves as a preliminary step to evaluate diet and/or PA policies in Germany. It will further contribute to a standardized framework for diet and/or PA policy evaluation and aims to improve transparency for decision makers.

† This is the original text of the proposal which was copied without changes and only minimally adjusted for typesetting in LaTeX.

- Following this process a model will be adapted and used to evaluate exemplary policies addressing diet and/or PA regarding their effect on health outcomes with focus on cardiometabolic diseases including their risk factors, complications and costs in Germany. Further application across the EU will be assessed and promoted with the JPI HDHL-PEN collaborators. The last two steps will comprise two publications.

Relevance and Implications: Available methodology for the simulation of long-term health economic effects can be leveraged to provide a robust evidence base for policymakers and other stakeholders in the EU. This is key to improve population health and to address the burden of cardiometabolic diseases. With the results of this dissertation an evidence-based discussion of the available health policies for diet and/or PA is supported and ideally translation, as well as conceptualization of future policies regarding data requirements for evaluation and the evaluation process itself is improved.

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G. Contribution to the journal *Lebendige Wissenschaft Diabetologie - Innovationen und Auszeichnungen 2024*

The article entitled "*Bevölkerungsbasierte Prävention von Adipositas und Typ 2 Diabetes am Beispiel einer Steuer auf zuckergesüßte Getränke*", which is included below, was an invited contribution for the (non-scientific) journal "Lebendige Wissenschaft Diabetologie - Innovationen und Auszeichnungen 2024" which was published May 2nd 2024 by the *Alpha Informationsgesellschaft mbH* for the annual conference of the German Diabetes Association (*Deutsche Diabetes Gesellschaft*) taking place in Berlin from May 8th to May 11th 2024. The invitation was related to the publication of our modeling study to evaluate the health and economic impact of SSB taxation in Germany (see Publication 3).

Bevölkerungsbasierte Prävention von Adipositas und Typ 2 Diabetes am Beispiel einer Steuer auf zuckergesüßte Getränke

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DIE GESAMTGESELLSCHAFTLICHEN GESUNDHEITLICHEN UND ÖKONOMISCHEN EFFEKTE VON ADIPOSITAS

Die weltweite Prävalenz von Übergewicht (Body Mass Index ≥ 25 kg/m²) und Adipositas (Body Mass Index ≥ 30 kg/m²) ist über die letzten Jahrzehnte enorm gestiegen und stellt eine der bedeutendsten Herausforderungen für die globale öffentliche Gesundheit im 21. Jahrhundert dar [1,2]. Nach Schätzungen aus der Studie Gesundheit in Deutschland aktuell (GEDA) 2019/2020 des Robert Koch-Instituts sind in Deutschland über 50 % der Bevölkerung übergewichtig und 19 % der Männer und Frauen, erfüllen die Kriterien einer Adipositas Diagnose [3]. Vorausberechnungen verdeutlichen, dass die Prävalenz von Adipositas in den nächsten 20 Jahren auf über 30 % ansteigen könnte [4].

Die negativen gesundheitlichen Folgen von Übergewicht, und insbesondere schwerer Adipositas, sind klinisch und epidemiologisch ausführlich erforscht und belegt. Ein erhöhter Anteil an Fettgewebe, insbesondere Viszeralfett, stört eine Vielzahl an Stoffwechselprozessen und führt zu Bluthochdruck, Dyslipidämie, und eine erhöhte Insulinresistenz, die wiederum zu einem dauerhaft erhöhten Blutzuckerspiegel führt [5-7]. Diese Kombination von ungünstigen Faktoren, die auch als metabolisches Syndrom bezeichnet wird, erhöht das Risiko für Typ 2 Diabetes und verursacht kardiovaskuläre Folgeerkrankungen, wie Erkrankungen der Herzkranzgefäße und Schlaganfälle [8,9].

Durch diese gesundheitlichen Effekte verursachen Übergewicht und Adipositas erhebliche gesellschaftliche Kosten in den Gesundheits- und Sozialversicherungssystemen. Im Jahr 2019 wurde die globale wirtschaftliche Belastung durch Adipositas auf etwa 2,2 % des globalen Bruttoinlandsprodukts (BIP) geschätzt [10]. In Deutschland wurde diese mit rund 63 Milliarden Euro (~3 % des BIP im Jahr 2010) ähnlich hoch quantifiziert [11]. Diese ökonomischen Effekte bestehen zum einen aus hohen direkten Kosten für Diagnose und Therapie und zum anderen aus indirekten Kosten durch Produktivitätsverluste wie beispielsweise krankheitsbedingte Arbeitsausfälle und vorzeitige Verrentungen. Allein die Kosten von kardiovaskulären Erkrankungen sind in Deutschland für über 10 % der Gesundheitsausgaben verantwortlich und Personen mit Typ 2 Diabetes haben in Deutschland jährlich in etwa doppelt so hohe Versorgungskosten wie gleichalterige Personen ohne Typ 2 Diabetes [12-14]. Produktivitätsverluste verursachen in Deutschland und global ca. 30 – 50 % der gesamten ökonomischen Kosten [14,15].

LEBENSSTILFAKTOREN IN DER ENTWICKLUNG VON KARDIOMETABOLISCHEN ERKRANKUNGEN

Die wichtigsten Determinanten von Adipositas, Typ 2 Diabetes und kardiovaskulären Erkrankungen umfassen neben genetischen Prädispositionen und Umweltfaktoren vor allem Lebensstilfaktoren wie Bewegungsmangel und ungesunde Ernährungsgewohnheiten [6,16]. Letztere folgen zusätzlich einem ausgeprägten sozialen Gefälle, welches zu einer höheren Prävalenz in benachteiligten Bevölkerungsgruppen führt, die beispielsweise durch Armut und ein niedrigeres Bildungsniveau gekennzeichnet sind [17,18]. In Deutschland ist die Prävalenz von Adipositas in den niedrigsten Bildungsgruppen etwa doppelt so hoch wie in den höchsten [3]. Dies unterstreicht die multifaktorielle Natur dieser Erkrankungen und verdeutlicht die Notwendigkeit eines ganzheitlichen Ansatzes zur Prävention (und Behandlung).

Vor allem ungesunde Ernährungsweisen stellen einen der wichtigsten Risikofaktoren für Adipositas und kardiometabolische Folgeerkrankungen dar [16]. In Mitteleuropa sind etwa 27 % der vorzeitigen Todesfälle auf Ernährungsrisiken zurückzuführen [19]. Dies ist unter anderem als direkte Folge eines Ernährungssystems zu betrachten, welches energiereiche, oft stark verarbeitete Lebensmittel einfach und billig verfügbar macht und somit eine ungesunde Ernährungsweise fördert [16]. Ernährungsbezogene Risiken werden vor allem durch den übermäßigen Konsum von Lebensmitteln mit hohem Anteil an gesättigten Fetten, Salz und einfachen

Zuckern, in Verbindung mit einer nicht-ausreichenden Zufuhr von Früchten, Gemüse, Vollkornprodukten und ungesättigten Fetten, erhöht [16,20]. Hierbei sind sowohl Aspekte der Qualität als auch der Quantität der Ernährung relevant, wenngleich vor allem letztere durch ein potenzielles Ungleichgewicht in der Energiebilanz einen entscheidenden Einfluss auf die Entwicklung von Übergewicht hat [21]. Die Forschung zeigt außerdem, dass der starke Anstieg im Verzehr von hochverarbeiteten Lebensmitteln im Zuge einer globalen Ernährungstransition durch optimierte Geschmacksprofile, Zusatzstoffe, und Verarbeitungstechniken Sättigungsgefühl und Kalorienaufnahme teils entkoppelt [22-24].

DIE GESUNDHEITLICHEN AUSWIRKUNGEN DES KONSUMS VON ZUGESETZTEM ZUCKER

Insbesondere die vielfältigen direkten und indirekten negativen Effekte des Konsums von Zucker sind sehr gut belegt [21,25,26]. Der Konsum von zuckergesüßten Getränken (aus dem Englischen: sugar-sweetened beverages) ist hier von besonderer Bedeutung, da über diese weltweit der Großteil des zugesetzten Zuckers konsumiert wird [27]. Zuckergesüßte Getränke sind nicht einheitlich definiert. Es werden unter dieser Bezeichnung jedoch meist nicht-alkoholische Getränke, die Süßungsmittel mit hoher Energiedichte (zum Beispiel Saccharose, Fructose-Glukose-Sirup) enthalten, zusammengefasst [27]. Problematisch ist hier vor allem, dass aufgrund des hohen Gehalts an flüssigen Kalorien, welche nicht zu einem nachhaltigen Sättigungsgefühl führen, eine positive Energiebilanz gefördert wird [16,27]. Langfristig führt dies zu einer Zunahme des Körpergewichts [28]. Darüber hinaus erhöht ein hoher Konsum von zugesetztem Zucker durch direkte Mechanismen (d.h. unabhängig vom Körpergewicht) das Risiko für Typ 2 Diabetes und andere metabolische Erkrankungen [29,30].

Aus diesen Gründen empfiehlt die Weltgesundheitsorganisation (WHO), dass der Anteil von Zucker an der gesamten Energieaufnahme 5 – 10 % nicht überschreiten sollte [31]. In den meisten Ländern, und auch in Deutschland, liegt der tatsächliche Konsum von zugesetztem und gesamten Zucker jedoch weit über diesem Schwellenwert [32,33]. Nach Daten der Wirtschaftsvereinigung Alkoholfreie Getränke (wafg) betrug der durchschnittliche pro-Kopf Konsum von zuckergesüßten Getränken in Deutschland im Jahr 2021 über 70 Liter [34]. Analysen der Nationalen Verzehrsstudie II verdeutlichen, dass der Konsum dieser Getränke vor allem unter jungen Männern am höchsten ist. Außerdem kann auch hier ein klarer Gradient entlang sozioökonomischer Charakteristika beobachtet werden [35].

DIE BESTEUERUNG ZUCKERGESÜSSTER GETRÄNKE ZUR PRÄVENTION VON ADIPOSITAS UND TYP 2 DIABETES

Deutschland und viele weitere Länder stehen somit vor der Herausforderung die Rahmenbedingungen für gesunde Ernährungsweisen zu schaffen und hierdurch die Sozialsysteme zu entlasten. Bevölkerungsbasierte Präventionsansätze besitzen ein großes Potenzial, um dies zu bewerkstelligen und werden international von Experten empfohlen [16,36]. Hierbei ist eine Kombination von sowohl Verhaltens- als auch Verhältnisprävention entscheidend. Vor allem das Potential von Verhältnisprävention wird in Deutschland nicht ausgeschöpft [37,38]. Verhältnispräventive Maßnahmen nehmen strukturelle Faktoren, wie beispielsweise Lebensmittelpreise oder die Ernährungsumwelt in den Blick und reduzieren im Gegensatz zu vielen verhaltenspräventiven Maßnahmen effektiver sozial-bedingte gesundheitliche Ungleichheiten [39]. Allerdings handelt es sich hierbei oft um Maßnahmen, die einer nationalen politischen Umsetzung bedürfen und ressortübergreifende Implikationen haben [36].

Zur Verringerung des Zuckerkonsums und zur Prävention von Adipositas und damit verbundenen Gesundheitsrisiken wird von der WHO eine Steuer auf zuckergesüßte Getränke empfohlen [40]. Eine solche Steuer kann als ökonomischer Anreiz dienen, dass Verbraucher weniger zuckergesüßte Getränke kaufen und somit weniger Zucker konsumieren [41]. Es wird empfohlen eine etwaige Steuer so zu gestalten, dass die Preise der besteuerten Getränke stark genug steigen, dass Verbraucher die Preisänderung wahrnehmen und, dass diese hoch genug ist, um eine tatsächliche Änderung im Kaufverhalten herbeizuführen [42]. Die WHO empfiehlt deshalb einen Steuersatz von mindestens 20 % [43]. Momentan erheben mehr als 60 Länder oder Städte spezifische Steuern mit unterschiedlicher Ausgestaltung auf zuckergesüßte Getränke. Am häufigsten bezieht sich die Besteuerung hierbei auf das

Volumen der Getränke (z.B. € 0,22 pro Liter in Finnland), seltener auf den Preis (z.B. Erhöhung der Mehrwertsteuer von 10 % auf 21 % in Spanien) [44]. Wenn die Höhe der Besteuerung zusätzlich am Zuckergehalt der Getränke ausgerichtet ist (z.B. in Frankreich und in Großbritannien), kann dies auch Anreize für eine Reformulierung der Produkte durch die Hersteller bieten. Studien zeigen, dass insbesondere solche gestaffelten Steuern effektiv zur Reduzierung des Zuckergehalts in den besteuerten Getränken beitragen können [45]. Unter einer gestaffelten Steuer wird dabei verstanden, dass die Besteuerungshöhe anhand des Zuckergehalts der Getränke mit festgelegten Grenzwerten variiert (zum Beispiel £ 0,18 pro Liter für Getränke mit einem Zuckergehalt von 5 bis 8 g pro 100 ml und £ 0,24 pro Liter für Getränke mit mehr als 8 g Zucker pro 100 ml, wie es beim Soft Drinks Industry Levy in Großbritannien der Fall ist [46]).

Die bisherige Evidenz zur Wirksamkeit von Steuern auf zuckergesüßte Getränke ist heterogen und zu einem gewissen Grad abhängig davon, welche Endpunkte betrachtet werden. Eine kürzlich publizierte Meta-Analyse von Beobachtungsstudien, welche die Effekte von bereits eingeführten Steuern auf zuckergesüßte Getränke zusammenfasst, zeigt eindrücklich, dass diese Maßnahmen tatsächlich zu einer Preiserhöhung und einem Rückgang der Verkaufszahlen geführt haben. Gleichzeitig sind keine umfangreichen Ausweichbewegungen der Verbraucher auf andere ungesunde Lebensmittel beobachtet worden [45]. Die Studienlage zur Veränderung des Konsums und zu mittelfristigen Effekten auf das Körpergewicht ist allerdings weniger eindeutig. Dies ist insbesondere durch eine höhere Anfälligkeit dieser Endpunkte für Messfehler und eine geringere Datenverfügbarkeit zu erklären [41]. Dennoch zeigen erste quasi-experimentelle Analysen aus Großbritannien und den Vereinigten Staaten, dass positive Effekte auf das Körpergewicht bei Jugendlichen, vor allem Mädchen, zu erwarten sind [47,48].

Die Reduktion des Zuckerkonsums durch bevölkerungsbasierte Maßnahmen, wie die Besteuerung zuckerhaltiger Getränke, könnte auch in Deutschland einen wesentlichen Beitrag zur Verbesserung der öffentlichen Gesundheit leisten [38]. Im Jahr 2020 hat ein umfassender Bericht des Wissenschaftlichen Beirat für Agrarpolitik, Ernährung und gesundheitlichen Verbraucherschutz (WBAE) des Bundesamtes für Landwirtschaft und Ernährung (BMEL) eine nationale, systemweite Strategie für nachhaltige und gesunde Ernährung zur Bekämpfung von Adipositas und zur Verbesserung des CO_2-Fußabdrucks des deutschen Ernährungssystems skizziert [49]. Dieser Bericht hat neben weiteren Maßnahmen auch die Einführung einer Steuer auf zuckerhaltige Süßgetränke, die nach internationalem Vorbild linear mit dem Zuckergehalt steigt, als sinnvolle politische Maßnahme hervorgehoben [49]. Andere Nichtregierungsorganisationen und Forschungsverbände wie die Deutsche Adipositas Gesellschaft (DAG), die Deutsche Diabetes Gesellschaft (DDG), beide Mitglieder der Deutschen Allianz Nicht-Übertragbare Krankheiten (DANK), und foodwatch unterstützen diesen Vorschlag [50,51].

In Deutschland setzt die Bundesregierung im Rahmen der Nationalen Reduktionsstrategie hingegen auf freiwillige Selbstverpflichtungen der Lebensmittelindustrie. Diese haben das Ziel, den Zuckergehalt in Getränken von 2015 bis 2025 um 15 % zu reduzieren [52]. Eine Evaluation dieser Strategie hat gezeigt, dass dieser Ansatz die angestrebte Reduktion nicht erreicht hat. Während in Deutschland in diesem Zeitraum der durchschnittliche Zuckergehalt in zuckergesüßten Getränken nur um 2% gesunken ist, ist dieser im selben Zeitraum in Großbritannien, wo 2018 eine gestaffelte Steuer eingeführt wurde, um fast 30 % gefallen [52].

HERAUSFORDERUNGEN IN DER EVALUATION VON BEVÖLKERUNGSBASIERTEN ERNÄHRUNGSMASSNAHMEN

Für den Entscheidungsprozess benötigen Entscheidungsträger die bestmögliche kontext-spezifische wissenschaftliche Evidenz, die zum Zeitpunkt der Entscheidung möglich ist. Allerdings stellt die robuste wissenschaftliche Evaluation von bevölkerungsbasierten Ernährungsmaßnahmen aufgrund der Komplexität von Interaktionen zwischen Ernährungsumwelt und -verhalten, sowie von intendierten und nicht-intendierten Effekten eine methodische Herausforderung dar [53,54]. Zum einen können bevölkerungsbasierte Maßnahmen im Gegensatz zu typischen klinischen Interventionen – wie neuen Medikamenten – nicht in einem kontrollierten Umfeld randomisiert werden und die kausale Attribution von Effekten ist schwieriger. Zum anderen werden die potenziellen positiven gesundheitlichen Effekte in den entscheidungsrelevanten Endpunkten, wie beispielsweise der Inzidenz von Typ 2 Diabetes, aufgrund der langsamen Ätiologie dieser Erkrankungen nur über lange Zeiträume realisiert [53].

Zumindest für kurz- und mittelfristig relevante Endpunkte kann diesen Herausforderungen mit quasiexperimentellen Methoden und Daten aus Ländern, in welchen entsprechende Maßnahmen bereits eingeführt wurden, begegnet werden. Im Fall einer Steuer auf zuckergesüßte Getränke sind dies beispielsweise Verkaufszahlen, der Konsum oder der Zuckergehalt der besteuerten Getränke. Quasiexperimentelle Ansätze nutzen hierbei zeitlich, räumlich und personenbezogene Unterschiede in der Implementierung von Maßnahmen, um mit modernen statistischen Methoden kausale Schlüsse ziehen zu können [53]. Allerdings stößt auch diese Methodik bei langen Zeiträumen und weniger unmittelbaren Endpunkten an ihre Grenzen und kann zudem nur angewandt werden, wenn eine politische Maßnahme bereits in Kraft ist [53,55].

Um evidenzbasierte politische Entscheidungen dennoch zu ermöglichen, sind epidemiologische und gesundheitsökonomische Simulationsmodelle ein wichtiges Werkzeug. Mit Hilfe dieser Modelle können die potenziellen langfristigen gesundheitlichen und ökonomischen Auswirkungen von bevölkerungsbasierten Präventionsansätzen vorhergesagt werden [55,56]. Um dies zu erreichen, kombinieren diese eine Vielzahl von nationalen epidemiologischen und ökonomischen Daten aus bevölkerungsbasierten Umfragen, Registern, und klinischen Studien mit medizinischem Wissen und robuster wissenschaftlicher Evidenz zu gesundheitlichen Risikofaktoren und Erkrankungen in einem mathematischen Modell das Gesundheit, Krankheit und diesbezügliche ökonomische Implikationen in einer Bevölkerung detailgetreu über die Zeit simuliert. Dieses Modell kann anschließend für die Analyse verschiedener Szenarien genutzt werden, in denen der langfristige Einfluss einer Maßnahme auf Gesundheit, Lebensqualität und Krankheitskosten unter Berücksichtigung der zugrundeliegenden Unsicherheiten simuliert wird. Die daraus gewonnenen Ergebnisse können dann Entscheidungsträgern als wichtige Grundlage dienen [55,57].

MODELLIERUNG EINER STEUER AUF ZUCKERGESÜSSTE GETRÄNKE IN DEUTSCHLAND

Um die potenziellen gesundheitlichen und ökonomischen Effekte von Präventionsmaßnahmen in Deutschland abzuschätzen haben wir an der Professur für Public Health und Prävention der Technischen Universität München das erste auf Deutschland angepasste epidemiologisch-ökonomische Mikrosimulationsmodell, $\text{IMPACT}_{\text{NCD}}$ Germany, entwickelt und umfassend validiert. Das Modell wurde von 2021 bis 2023 im Rahmen des europäischen Policy Evaluation Network (PEN) Projektes (www.jpi-pen.eu) zusammen mit Kolleg:innen der Universität Liverpool in Großbritannien aufgebaut. $\text{IMPACT}_{\text{NCD}}$ Germany ist ein stochastisches, dynamisches Modell, welches ein realistisches Abbild der deutschen Erwachsenenbevölkerung in diskreten Zeitabständen (Jahre) simuliert.

Mit diesem Modell haben wir die langfristigen Effekte verschiedener Besteuerungsszenarien auf zuckergesüßte Getränke in der deutschen Erwachsenenbevölkerung von 2023 bis 2043 modelliert [58]. Die untersuchten Szenarien orientierten sich hierbei unter anderem an internationalen Empfehlungen und der in Großbritannien verabschiedeten gestaffelten Herstellerabgabe (Soft Drinks Industry Levy): (Szenario 1) eine 20%ige Wertsteuer (englisch: *ad-valorem tax*) auf zuckergesüßte Getränke die zu einer verringerten Nachfrage führt;

1

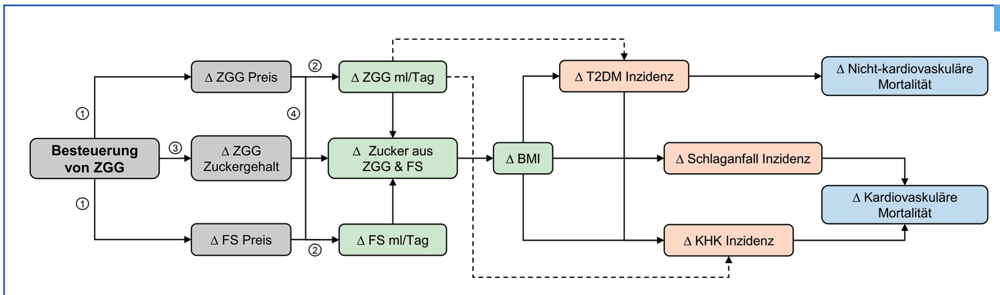

Abbildung 1
■ *Modellstruktur von $\text{IMPACT}_{\text{NCD}}$ Germany zur Modellierung einer Steuer auf zuckergesüßte Getränke (Reproduziert und übersetzt von Emmert-Fees et al., PLOS Medicine, 2023 [58]). Darstellung aller modellierten Pfade. Gestrichelte Pfeile repräsentieren direkte Effekte von zuckergesüßten Getränken (ZGG), die in Sensitivitätsanalysen ausgeschlossen wurden. Graue Kästen zeigen modellierte Effekte der Besteuerung und die entsprechenden nummerierten Pfeile bezeichnen zugrundeliegende modellierte Mechanismen: (1) Ökonomische Erkenntnisse legen nahe, dass Produzenten von ZGG einen gewissen Anteil der Besteuerung in Form von erhöhten Preisen an Verbraucher weitergeben. (2) Höhere Preise für ZGG führen zu einer Veränderung im Konsum basierend auf der Eigenpreiselastizität der Nachfrage nach ZGG. (3) Gestaffelte Besteuerung mit unterschiedlichen Steuersätzen je nach Zuckergehalt der ZGG motiviert Hersteller zur Reformulierung hin zu niedrigerem Zuckergehalt, um die Steuerlast zu vermeiden. (4) Höhere Preise für ZGG führen potenziell zur Substitution mit ähnlichen Gütern wie Fruchtsaft, basierend auf deren Kreuzpreiselastizität der Nachfrage. Grüne Kästen zeigen Risikofaktoren. Orange und blaue Kästen zeigen Krankheits- und Mortalitätsendpunkte. Δ, »Veränderung in«; BMI, Body-Mass-Index; FS, Fruchtsaft; KHK, koronare Herzkrankheit; ml, Milliliter; ZGG, zuckergesüßte Getränke; T2DM, Diabetes mellitus Typ 2.*

(Szenario 2) eine gestaffelte Steuer nach britischem Vorbild, die durch Reformulierung zur Verringerung des Zuckergehalts von zuckergesüßten Getränken um 30 % führt [58]. **Abbildung 1** zeigt die im Modell angenommene kausale Struktur und definiert die modellierten klinisch-epidemiologischen Mechanismen.

Die Ergebnisse dieser Studie zeigen, dass eine 20%ige Wertsteuer auf zuckergesüßte Getränke (Szenario 1) den Konsum von zugesetztem Zucker in der deutschen Erwachsenenbevölkerung im Schnitt um 1 g/Tag (95%-Unsicherheitsintervall [0,05, 1,65]) senken könnte. Eine gestaffelte Abgabe nach britischem Vorbild (Szenario 2) könnte sogar zu einer Zuckerreduktion um 2,34 g/Tag (95%-UI [2,32, 2,36]) führen. Es ist zu beachten, dass dies Durchschnittswerte sind und der Rückgang des Zuckerkonsums vor allem bei Personen mit hohem Süßgetränkekonsum um ein Vielfaches höher ausfällt. Durch die daraus resultierende Verringerung von Adipositas, Typ 2 Diabetes und Herz-Kreislauf-Erkrankungen könnten in Deutschland je nach Szenario über die nächsten 20 Jahre 106.000 (95%-UI [57.200, 153.200]) bis 192.300 (95%-UI [130.100, 254.200]) qualitätsadjustierte Lebensjahre (QALYs) gewonnen werden. Insbesondere würden 132.100 (95%-UI [61.700, 202.900]) bis 244.100 (95%-UI [118.200, 365.300]) Fälle von Typ 2 Diabetes verhindert oder verzögert werden. Dadurch könnten aus gesellschaftlicher Perspektive bis 2043 unter einer 20%igen Wertsteuer Kosten in Höhe von € 9,6 Milliarden (95%-UI [4,7, 15,3]) bzw. € 16,0 Milliarden (95%-UI [8,1, 25,5]) unter einer gestaffelten Steuer eingespart werden [58]. Hierbei würden etwa € 2 bzw. € 4 Milliarden direkt im deutschen Gesundheitssystem eingespart werden. Um die Stabilität der Ergebnisse zu überprüfen, wurde in Kooperation mit Kolleg:innen der Universität Oxford zusätzlich ein zweites Simulationsmodell (PRIMEtime) auf Deutschland angepasst und die identischen Besteuerungsszenarien modelliert. Die Ergebnisse der beiden Modelle unterscheiden sich nur geringfügig.

FAZIT

Die Besteuerung zuckergesüßter Getränke hat ein bedeutendes Potenzial, um den Konsum von zugesetztem Zucker zu reduzieren und dadurch einen Beitrag zur Prävention von kardiometabolischen Erkrankungen zu leisten. Angesichts der steigenden Prävalenz ernährungsbedingter Krankheiten wie Adipositas, Typ 2 Diabetes und Herz-Kreislauf-Erkrankungen ist es entscheidend, effektive bevölkerungsbasierte Maßnahmen zu ergreifen. Während die Implementierung solcher politischer Maßnahmen Herausforderungen mit sich bringt, unterstreicht die vorhandene Evidenz deren großen potenziellen gesundheitlichen und ökonomischen Nutzen. Die Ergebnisse von epidemiologisch-ökonomischen Simulationsstudien können hierbei wertvolle Einblicke bieten, um Entscheidungsträgern zeitnah wichtige Informationen und Handlungsempfehlungen bereitzustellen und letztendlich die Gesundheit der Bevölkerung zu fördern. Durch die Anwendung eines modernen Mikrosimulationsmodells haben wir unter Berücksichtigung relevanter Unsicherheiten die potentiellen Effekte von verschiedenen Szenarien für die Besteuerung von zuckergesüßten Getränken in Deutschland simuliert. Wir kommen zu dem Schluss, dass eine gestaffelte Steuer nach britischem Vorbild voraussichtlich den größten gesundheitlichen und wirtschaftlichen Effekt auf Bevölkerungsebene hätte [58]. Es ist davon auszugehen, dass mit diesem Ansatz über die kommenden beiden Jahrzehnte hunderttausende gesunde Lebensjahre gewonnen und Milliarden an volkswirtschaftlichen Kosten vermieden werden könnten.

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Karl Emmert-Fees *ist seit März 2021 wissenschaftlicher Mitarbeiter am Lehrstuhl für Public Health und Prävention an der TUM unter der Leitung von Prof. Dr. Michael Laxy. Parallel dazu ist er Doktorand am Institut für Epidemiologie des Helmholtz Zentrums München.*
Seit 2019 ist er teil des PhD-Programms »Medical Research in Epidemiology and Public Health« der Munich Medical Research School an der LMU München. Zuvor absolvierte er seinen Master of Science in Public Health an der LMU München.

In seiner Doktorarbeit beschäftigt sich Karl mit der Evaluation von populationsbasierten Politiken zur Reduzierung der gesundheitlichen und wirtschaftlichen Belastung durch nicht übertragbare Krankheiten. International ist er außerdem an Projekten am Emory Global Diabetes Research Center an der Emory University in Atlanta, Georgia beteiligt, die sich mit kardiometabolischer und psychischer Gesundheit befassen.

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Work Experience

Research Associate **Since 2021**
Professorship of Public Health and Prevention, School of Medicine and Health, Technical University of Munich

Conduct of doctoral research project on the evaluation of diet policies using simulation modeling methods in Germany, including the development of the IMPACT$_{\mathrm{NCD}}$ Germany microsimulation model (github.com/kalleEF/IMPACT-NCD-Germany). Further work on non-communicable disease prevention, health inequalities, and public health economics particularly related to diabetes, depression, and nutrition. Teaching of social determinants of health, public health, and intervention evaluation methods.

Guest Researcher **Since 2020**
Institute of Epidemiology, Helmholtz Munich

Visiting Researcher **2022**
Nuffield Department of Population Health, University of Oxford, United Kingdom

Research stay with Professor Peter Scarborough to work on comparative simulation modeling of population-based diet policies using the PRIMEtime model.

Visiting Researcher **2022**
Department of Public Health, Policy & Systems, University of Liverpool, United Kingdom

Research stay with Professor Martìn O'Flaherty and Dr. Chris Kyrpidemos to adapt the IMPACT$_{\mathrm{NCD}}$ microsimulation to Germany to enable the assessment of the health and economic impact of population-based diet policies in Germany.

Research Associate **2019-2020**
Institute for Health Economics and Healthcare Management (discontinued), Helmholtz Munich

Development of proposal for and start of doctoral research project on the evaluation of diet policies using simulation modeling methods in Germany within the EU-funded Policy Evaluation Network (PEN) project (www.jpi-pen.eu). Statistical analysis of the INDEPENDENT randomized trial which evaluated the effectiveness of a collaborative care intervention for patients with type 2 diabetes and depression (doi:10.1001/jama.2020.11747).

Visiting Fellow **2018**
Emory Global Diabetes Research Center (EGDRC), Emory University, Atlanta, GA, USA

Support of Michael Laxy during is Harkness Fellowship in Health Care Policy and Practice. Project related to the impact of the expansion of Medicaid coverage in the USA under the Affordable Care Act 2010 on diabetes care using NHANES and NHIS data. Application of econometric methods to public health and epidemiological topics.

Student Research Assistant **2017-2018**
Institute for Medical Information Processing, Biometry and Epidemiology (IBE), Ludwig-Maximilian University of Munich

Correction of student assignments in the course *Epidemiology I* and support with administrative tasks.

Student Research Assistant **2016-2018**
Institute for Health Economics and Healthcare Management, Helmholtz Zentrum München

Support for several research projects in the field of diabetes prevention and health economic analyses related to diabetes, including literature research. Support of a doctoral student in the design and conduct of a systematic literature review on the impact of diabetes on labor market participation (doi:10.1186/s12889-018-6324-6).

Student Research Assistant **2013-2015**
Chair of Sociology and Empirical Social Science, Friedrich-Alexander University of Erlangen-Nuremberg

Tutor for exercises in the courses *Empirical Social Science I + II* and *Empirical Methods and Statistics* using Stata.

Education

Ph.D. Medical Research in Epidemiology and Public Health **Since 2019**
Institute for Medical Information Processing, Biometry and Epidemiology (IBE), Ludwig-Maximilians University of Munich, Pettenkofer School of Public Health

Doctoral research project on the application of simulation modeling methods to evaluate diet policies in Germany.

Master of Science in Public Health **2016-2019**
Ludwig-Maximilians University of Munich

Courses in epidemiology, public health, health economics, behavioral sciences, and advanced quantitative methods. Master thesis on the cost-effectiveness of a collaborative care intervention for diabetes comorbid depression in India (doi:10.2337/dc21-2533).

Bachelor of Arts in Sociology and Economics **2012-2015**
Friedrich-Alexander University of Erlangen-Nuremberg

Courses in statistics, sociology, social science research, and economics with a specialization in health. Bachelor thesis on the role of employment status on sex differences in informal care across Europe.

Awards

RIGorous inference in Obesity Research (RIGOR) Award 2023
Award from the NIH-funded short course Strengthening Causal Inference in Behavioral Obesity Research of the Indiana University School of Public Health-Bloomington for the paper "*Estimating the impact of nutrition and physical activity policies with quasi-experi-mental methods and simulation modelling: an integrative review of methods, challenges and synergies*".

Second best mini-oral presentation at the 16th Symposium of the International Diabetes Epidemiology Group (IDEG), 2019 in Seoul, South Korea

Presentation: *Cost-effectiveness of a Collaborative Care Intervention for Diabetes Co-morbid Depression in India: Analysis of the Integrating Depression and Diabetes Treatment (INDEPENDENT) Trial.*

Ad hoc reviews

Scientific Journals
Journal of Medical Economics, Journal of Population Ageing, Public Health Nutrition, Advances in Nutrition, Deutsches Ärzteblatt International, Global Health Research and Policy, BMC Public Health

Technical skills

Statistical programming	*R*, *Stata*, *SAS*
Other	*Markdown, Git*, LaTeX, *Microsoft Office*

Languages

German	Native
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French	A1

I. Affidavit

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Affidavit

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I hereby declare, that the submitted thesis entitled

Evaluating the health and economic impact of population-based diet policies in Germany: Development, application, and comparison of simulation modeling methods

is my own work. I have only used the sources indicated and have not made unauthorised use of services of a third party. Where the work of others has been quoted or reproduced, the source is always given.

I further declare that the dissertation presented here has not been submitted in the same or similar form to any other institution for the purpose of obtaining an academic degree.

Munich, 01.10.2024

Place, Date

Karl Maria Friedemann Emmert-Fees

Signature doctoral candidate

J. Confirmation of congruency

Confirmation of congruency between printed and electronic version of the doctoral thesis

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I hereby declare that the electronic version of the submitted thesis, entitled

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is congruent with the printed version both in content and format.

Munich, 01.10.2024

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