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OPTIMIZING SCHOOL MEALS TODAY: A PATHWAY TO SUSTAINABLE DIETARY HABITS TOMORROW

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Optimizing school meals today: a pathway to sustainable dietary habits tomorrow

THESIS FOR DOCTORAL DEGREE (Ph.D.)

By

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ز گهواره تا گور دانش به جو

Search for knowledge, from the cradle to the grave
(Old Persian proverb)

POPULAR SCIENCE SUMMARY OF THE THESIS

The food we eat is one of the major contributors to climate change and ill-health globally. Now the question is, how can we achieve dietary shifts in order to halt these effects? School meals can reach children of every socioeconomic background and hold a near-unique potential to foster sustainable dietary habits in the younger generation, which can persist into adulthood. This thesis therefore explored a pathway to designing and introducing children to climate friendly, nutritious, affordable and culturally appropriate—i.e. sustainable—school lunches.

Study I assessed the importance of school lunches to children's diets in Sweden. Intakes of energy, nutrients and foods were calculated and compared between girls and boys as well as by pupils' parental education. We found that the school lunch provides pupils with an important source of foods such as vegetables and fish. Boys were found to consume more red/processed meat but less fiber and vegetables than girls. Differences in dietary intake based on pupils' parental education suggests that school meals can play a role in leveling out social inequalities in dietary intake.

Study II developed a holistic strategy for designing sustainable school meals with linear optimization. This mathematical modeling technique helped us to achieve the right combination of foods for a nutritious school food supply that was similar in terms of composition and cost but 40% lower in climate impact as compared to the usual food supply. The applied strategy did not exclude any food types. However, the total amount of animal products declined whereas the share of plant-based foods increased. Its acceptability in practice was to this point still unknown.

Study III used the developed optimization strategy from Study II to design a new sustainable 4-week school lunch menu, which was introduced in three Swedish primary schools. We aimed to study the acceptance of this new menu among pupils by keeping track of the daily food waste and consumption during the time when the menu was served. Pupils also answered a questionnaire which measured their school lunch satisfaction before as well as by the end of the intervention. The new sustainable menu did not increase food waste or change pupils' consumption of or satisfaction with school lunches.

Study IV used interviews to explore pupils' and kitchen staff's experiences with the introduction of the new menu as well as to identify challenges and opportunities to successfully introducing sustainable school meals at scale. Kitchen staff highlighted the lack of financial resources, equipment and time as a challenge. Pupils and kitchen staff also discussed the difficulty of providing meals that children are not used to eating. However, they also saw opportunities in increasing children's exposure to plant-based foods and in making pupils, kitchen staff and other actors more involved in the process of introducing sustainable school meals.

I hope that this thesis can show you how integrated methods and actions can form one promising pathway to achieve sustainable dietary habits in the young generation that could help to secure both human and planetary health needs.

RESUMEN DE LA TESIS

Los alimentos que consumimos son uno de los principales contribuyentes al cambio climático y la mala salud a nivel mundial. Ahora la pregunta es, ¿cómo podemos lograr cambios en dietas para detener estos efectos? Las comidas escolares pueden llegar a niños de todos los orígenes socioeconómicos. También tienen un potencial casi único para fomentar hábitos alimentarios sostenibles en las generaciones más jóvenes, que pueden persistir hasta la edad adulta. Por lo tanto, esta tesis exploró un camino para introducir almuerzos sostenibles en la dieta de los niños.

Estudio I evaluó la importancia de los almuerzos escolares para la dieta de los niños en Suecia. Las ingestas de energía, nutrientes y alimentos se calcularon y compararon entre niñas y niños, así como según la educación de los padres de los alumnos. Descubrimos que el almuerzo escolar proporciona a los niños una fuente importante de alimentos tales como verduras y pescado. Se encontró que los niños consumían más carne roja/procesada pero menos fibra y vegetales que las niñas. Las diferencias en la ingesta dietética basadas en la educación de los padres de los alumnos sugieren que las comidas escolares pueden contribuir a nivelar las desigualdades sociales en el consumo de alimentos.

Estudio II desarrolló una estrategia holística para diseñar comidas escolares sostenibles con optimización lineal. Esta técnica matemática nos ayudó a lograr la combinación correcta de alimentos para un suministro alimenticio escolar nutritivo que era similar, en términos de composición y costo, pero un 40% más bajo en impacto climático en comparación con el suministro de alimentos habitual. La estrategia aplicada no excluyó ningún tipo de alimento. Sin embargo, la cantidad total de productos animales disminuyó mientras que la proporción de alimentos de origen vegetal aumentó. Su aceptabilidad en la práctica era hasta el momento desconocida.

Estudio III utilizó la estrategia de optimización desarrollada a partir del Estudio II para diseñar un nuevo menú de almuerzo escolar sostenible de 4 semanas, que se introdujo en tres escuelas primarias suecas. Nuestro objetivo era estudiar la aceptación de este nuevo menú entre los alumnos haciendo un seguimiento del desperdicio y consumo diario de alimentos durante el tiempo en que se sirvió el menú. Los alumnos también respondieron un cuestionario que midió su satisfacción con el almuerzo escolar antes y al final de la intervención. El nuevo menú sostenible no aumentó el desperdicio de alimentos ni cambió el consumo o la satisfacción de los alumnos con los almuerzos escolares.

Estudio IV utilizó entrevistas para explorar las experiencias de los alumnos y el personal de cocina con la introducción del nuevo menú, así como para identificar desafíos y oportunidades para introducir con éxito comidas escolares sostenibles a escala. El personal de cocina destacó la falta de recursos económicos, equipos y tiempo como un desafío. Tanto los alumnos como el personal de cocina también expusieron la dificultad de servir comidas que los niños no están acostumbrados a comer. Sin embargo, también reconocieron oportunidades para aumentar la exposición de alimentos de origen vegetal a los alumnos y hacer que estos, el personal de cocina y otros actores participaran más en el proceso de introducción de comidas escolares sostenibles.

Espero que esta tesis pueda mostrarles cómo los métodos y acciones integrados pueden formar un camino prometedor para lograr hábitos alimentarios sostenibles en la generación joven y así ayudar a satisfacer las necesidades de salud tanto humana como planetaria.

ABSTRACT

Food production and consumption substantially contribute to climate change and disease. School meals can reach children of every socioeconomic background and hold a near-unique potential to foster sustainable dietary habits in the young generation in both the short and long term. This thesis explored a pathway to designing and introducing children to climate friendly, nutritious, affordable and culturally appropriate—i.e. sustainable—school lunches.

Study I explored the importance of school lunches to children's overall diets in Sweden. Dietary intakes of nutrients and food groups were calculated and compared between girls and boys as well as by pupils' parental education. School lunches accounted for almost half of pupils' vegetable intakes. The nutrient density was higher, and energy density lower, at lunch compared to foods consumed during the remaining weekday. Boys had higher intakes of red/processed meat, but lower intakes of dietary fiber and vegetables than girls. Differences in dietary intake based on pupils' parental education suggests that school meals can play a role in compensating for poorer dietary quality in the home environment.

Study II aimed to develop a holistic linear optimization strategy for achieving a sustainable Swedish school food supply. The developed strategy reduced greenhouse gas emissions (GHGE) from the school food supply by 40% with only small changes to the observed supply while also ensuring nutritional adequacy and affordability. Cost was reduced or comparable to baseline in all modeled solutions. Constraints applied to achieve higher levels of similarity to the observed supply prevented the linear optimization model's capacity to reduce GHGE.

Study III combined the optimization strategy developed in Study II with meal planning to design a sustainable 4-week lunch menu, which was tested in a school-based intervention study. Pre-post analyses evaluated the acceptability of the new menu by assessing effects changes to food waste, pupils' school lunch consumption, and their satisfaction with school meals. The new menu was introduced in three Swedish primary schools (grades 0-9) without increasing food waste or change pupils' consumption of, or satisfaction with, the school lunch.

Study IV qualitatively evaluated the acceptability of the new sustainable school lunch menu. Focus group discussions explored pupils' and kitchen staff's experiences with the new menu as well as potential barriers and facilitators to successful implementation of sustainable school meals at scale. Experiences with the intervention varied among pupils and kitchen staff. Barriers included pupils' unfamiliarity with eating plant-based meals and the lack of financial resources, adequate equipment and time for kitchen staff to prepare such meals. Aspects such as increased exposure to plant-based foods, knowledge, motivation, and stakeholder involvement were seen as facilitators to successful implementation.

The findings of this thesis highlight how integrated methods and actions implemented in the school meal system could help to foster sustainable dietary habits in children and thus contribute to meeting the needs of both human and planetary health.

SCIENTIFIC PAPERS INCLUDED IN THESIS

This thesis is an original contribution based on the four studies stated below:

I. **Eustachio Colombo P**, Patterson E, Elinder LS, Lindroos AK. The importance of school lunches to the overall dietary intake of children in Sweden: a nationally representative study. Public Health Nutrition. 2020;1–11.

II. **Eustachio Colombo P**, Patterson E, Elinder LS, Lindroos AK, Sonesson U, Darmon N, Parlesak A. Optimizing School Food Supply: Integrating Environmental, Health, Economic, and Cultural Dimensions of Diet Sustainability with Linear Programming. International Journal of Environmental Research and Public Health. 2019;16:3019.

III. **Eustachio Colombo P**, Patterson E, Lindroos AK, Parlesak A, Elinder LS. Sustainable and acceptable school meals through optimization analysis: an intervention study. Nutrition Journal. 2020;19.

IV. **Eustachio Colombo P**, Elinder LS, Patterson E, Parlesak A, Lindroos AK, Andermo S. Barriers and facilitators to successful implementation of sustainable school meals: a qualitative study of the OPTIMAT™-intervention. Under consideration (*International Journal of Behavioral Nutrition and Physical Activity*, 2021).

RELATED PUBLICATIONS

(Not included in the thesis)

I. **Eustachio Colombo P**, Elinder LS, Parlesak A, Lindroos AK, Patterson E. Fostering sustainable dietary habits through optimized school meals in Sweden – OPTIMAT. Public Health Panorama. 2017;3:557–60.

II. Elinder LS, **Eustachio Colombo P**, Patterson E, Parlesak A, Lindroos AK. Successful Implementation of Climate-Friendly, Nutritious, and Acceptable School Meals in Practice: The OPTIMAT™ Intervention Study. Sustainability. 2020;12:8475

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LIST OF ABBREVIATIONS

AR	Average requirement
ARD	Average relative deviation
ARRD	Average relative ratio deviation
BMI	Body mass index
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents
DEA	Data Envelopment Analysis
DRV	Dietary reference value
EER	Estimated energy requirement
FAO	Food and Agricultural Organization of the United Nations
FBDGs	Food based dietary guidelines
FGD	Focus group discussion
GHG	Greenhouse gas
GHGE	Greenhouse gas emissions
GWP	Global warming potential
HIC	High-income country
IPCC	Intergovernmental Panel on Climate Change
kcal	Kilocalorie
kJ	Kilojoule; (1 kcal equals to ~4.2 kJ)
LCA	Life Cycle Assessment
LMIC	Lower middle-income country
LP	Linear programming
MJ	Megajoule; 1000 kJ
MT	Megaton
N_2O	Nitrous oxide
NCD	Non-communicable disease
NNR	Nordic Nutrition Recommendations
QCA	Qualitative content analysis
RD	Relative deviation
RI	Recommended intake
RISE	Research Institutes of Sweden
RRD	Relative ratio deviation
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
SCT	Social Cognitive Theory
SDT	Self-determination theory
SES	Socioeconomic status
TRD	Total relative deviation
TRRD	Total relative ratio deviation
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WF	Water footprint
WHO	World Health Organization

1 INTRODUCTION

1.1 PART I: UNFOLDING THE PROBLEM

1.1.1 Human prosperity in the Anthropocene Epoch

From many perspectives, humanity has never been as prosperous as it is today. Undeniably, the global population has experienced unprecedented improvements with regards to health and wellbeing over the course of a considerably short period of time. During less than 70 years, global average life expectancy—a key proxy for the assessment of population health— has increased by almost 27 years, from 45.7 to 72.6 years (1). This noteworthy change has occurred in parallel with other rapid evolvements; the proportion of literate people in the world has more than doubled (2), global gross domestic product has almost quintupled (3), the share of the world population living in extreme poverty has declined more than five-fold (4), as has the proportion of children who die before reaching the age of five—all while the global population has more than tripled during a comparable period of time (5). These achievements are in turn a result of several other advancements in the political, social, and technological spheres of an increasingly globalized world (6). But the current feats in human prosperity have come at a cost; the growth and development of the human civilization have been realized at the expense of the health of the planet. Many of the advancements (albeit inequitable) that underpin this historically unparalleled human development are also the main contributors to environmental degradation which has only increased with a rapidly growing global population demanding food, water and other resources for its survival. It has been suggested that humanity has entered a new (yet not officially acknowledged) geological epoch called the Anthropocene, defined as the time period when human actions started to noticeably change the Earth system (7).

1.1.2 The Earth system and food in the Anthropocene Epoch

The Earth system is defined as ”*Earth's interacting physical, chemical, and biological processes consisting of land, oceans, atmosphere, and poles, and includes Earth's natural cycles—i.e. carbon, water, nitrogen, phosphorus and other cycles. Life, including human society, is an integral part of the Earth system and affects these natural cycles*” (8). Originating from the planetary boundaries framework (9), scientific limits for the safe operating space of food systems have recently been established for six key Earth system processes; land-system change; freshwater use; nitrogen cycling; phosphorus cycling; biodiversity loss and; climate change resulting from the emissions of greenhouse gases (8).

Food systems are complex systems as they involve the full array of actors and activities part of the production, accumulation, dispensation, transportation, and consumption of food being provided by agricultural, terrestrial or marine systems (10). Propelled by the increased need to nurture a rapidly expanding, wealthier and more urbanized global population, food systems in the Anthropocene Epoch are currently significant causes of change to the Earth's systemic processes (8). The agricultural sector occupies around 40% of all ice-free land surface (11) and contributes to around a quarter of all anthropogenic (i.e. originating from human activity) greenhouse gas emissions (GHGE) (12). The production of primary crops and in particular the expanding production of animal feed from cropland to meet increasing demands for meat drives land use and deforestation (13). Forests bind more carbon dioxide than any other category of land-cover and are vital for safeguarding terrestrial ecosystems (14,15). Hence, the clearing of land for food production interferes with many of the Earth's ecological functions, including climate stability (8). Agriculture is also responsible for approximately 70% of all human withdrawals of finite water resources from ground surface reserves resulting in growing freshwater scarcity in many regions of the world (16). In addition, the production and excessive use of fertilizers and manure for the production of food is disrupting natural nitrogen and phosphorous cycles (17). The anthropogenic application of these compounds is driving the eutrophication and acidification of the Earth's terrestrial and aquatic ecosystems, with adverse repercussions for biodiversity and ecosystem processes (18–20). Furthermore, food production compromises biodiversity, both directly and indirectly. Since the late 1960s, wild-harvested fish catch has diminished by approximately 1% annually as a result of unsustainable capture fishery (21). Clearing of land for agricultural purposes is the main driver of habitat and biodiversity loss with detrimental effects on the stability of the Earth system (22,23). Moreover, the destruction of habitat is bringing us in closer proximity with life and it´s increasing the risk of pathogens (such as SARS-CoV-2) jumping from animals to humans (6). By making use of no more than 2% of existent edible plant species food production systems are additionally driving biodiversity loss and thus also the loss of nutrients from high-nutrient plant species (24).

The global food system has contributed to the transgression of many of the planetary boundaries that define the safe space within which humanity is to operate to guarantee a stable Earth system (25). One of the Earth system processes that has already reached critical levels is the concentration of greenhouse gases in the Earth's atmosphere (26).

1.1.3 Greenhouse gas emissions and food

Greenhouse gases (GHG) enter our atmosphere through several pathways and in different chemical forms. These gases are part of the Earth system's natural cycles as they absorb and emit radiation in the atmosphere, hence creating the greenhouse effect keeping the global mean temperature at 15° C instead of -18° C without these gases (27). Anthropogenic GHGE are so far projected to have caused an increase of about 1.0° C in the average global temperature as compared to pre-industrial levels (28). In fact, it is estimated that the global average temperature on Earth would have reduced slightly over the past 100 years in the absence of human activity (29). If the average global temperature keeps increasing at today's rate, it could reach 1.5° C in a decade's time (28); something that will have damaging effects on many of the planet's life supporting ecosystems. **Figure 1.1** illustrates how several of the rapid global changes in population growth and per capita consumption described above have evolved in tandem with annual global GHGE, but also shows how the patterns of consumption differ between regions.

The increase in concentration of atmospheric GHG compared to preindustrial levels (30) can be partly attributed to the production of food for an increasing and wealthier world population (13). A majority (80-86%) of GHGE from food systems are caused by agricultural production (12). The three main types of GHG from food production to be mitigated under the Kyoto Protocol (31) are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (30). Carbon dioxide emissions from food production is mainly released from the soil when forests are cleared, from the burning of fossil fuels by agricultural machinery, the production of fertilizers, and from food processing and transport (8). Methane is mainly produced from the enteric fermentation of cellulose in ruminant livestock and from the fermentation of organic material in anaerobic environments, such as manure storages and rice paddies (30). Nitrous oxide mainly arises from microbial conversion of nitrogen in animal manure and through the application of synthetic fertilizers in the soil (17). These three GHG have different global-warming potential (GWP) which essentially refers to the potency of a greenhouse gas that has been emitted into the atmosphere to absorb energy and thus contribute to global warming (30). The average atmospheric residence time of different GHG varies between 1 to more than 50,000 years (30). Therefore, the Intergovernmental Panel on Climate Change (IPCC) provides science-based weighting factors to the different GHGs over different time periods: 20, 100 or 500 years (30). The GWP of one unit of methane or nitrous oxide is assessed in relation to the GWP of one unit of a reference gas, i.e. carbon dioxide. Using these weighting factors, a common measure can be generated and total GHGE of a food can then be expressed in carbon dioxide equivalents (CO_2eq).

About 70% of total global anthropogenic GHGE can be attributed to the livestock sector (17). This is largely a result of the fact that considerable areas of agricultural land are needed to produce feed for animals that are inefficient in converting this feed into meat for human consumption (32). Today, nearly 40% of all calories contained in cultivated crops are fed to animals and only 4% of the calories fed to animals are ultimately available to humans as animal products (32). Livestock also produces large amounts of methane through their digestive systems (directly) and trough their manure (indirectly) (30).

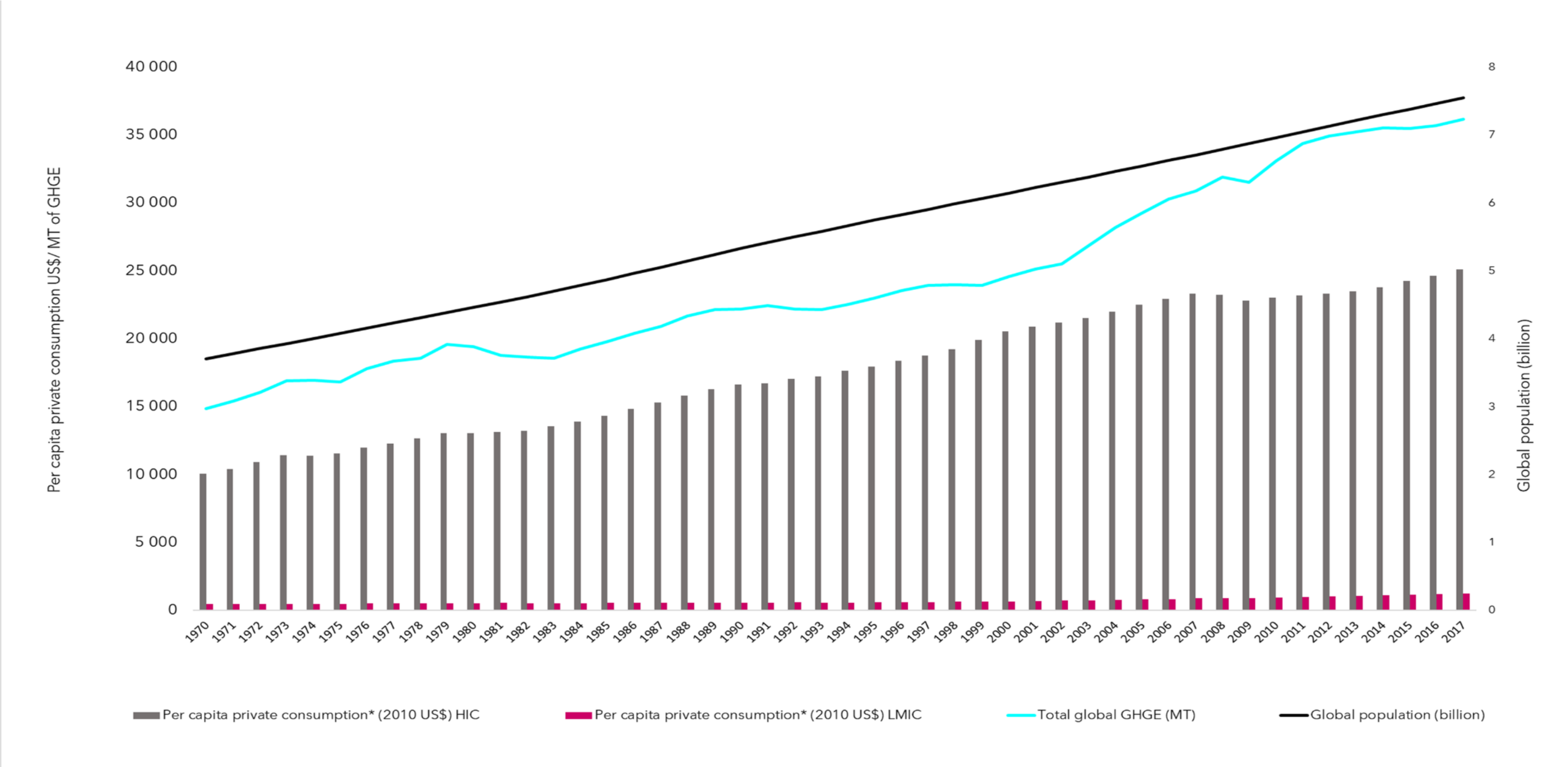

Figure 1.1. *Per capita private consumption, population growth and anthropogenic greenhouse gas emissions (1970-2017). *Market value of all goods and services, including durable products (such as cars, washing machines, and home computers), purchased by households. GHGE, greenhouse gas emissions; HIC, high income countries, LMIC, lower middle-income countries; MT, megaton. Sources of data: Per capita private consumption, The World Bank (33); Total GHGE, Our World in Data (34); Global population, Our World in Data (5).*

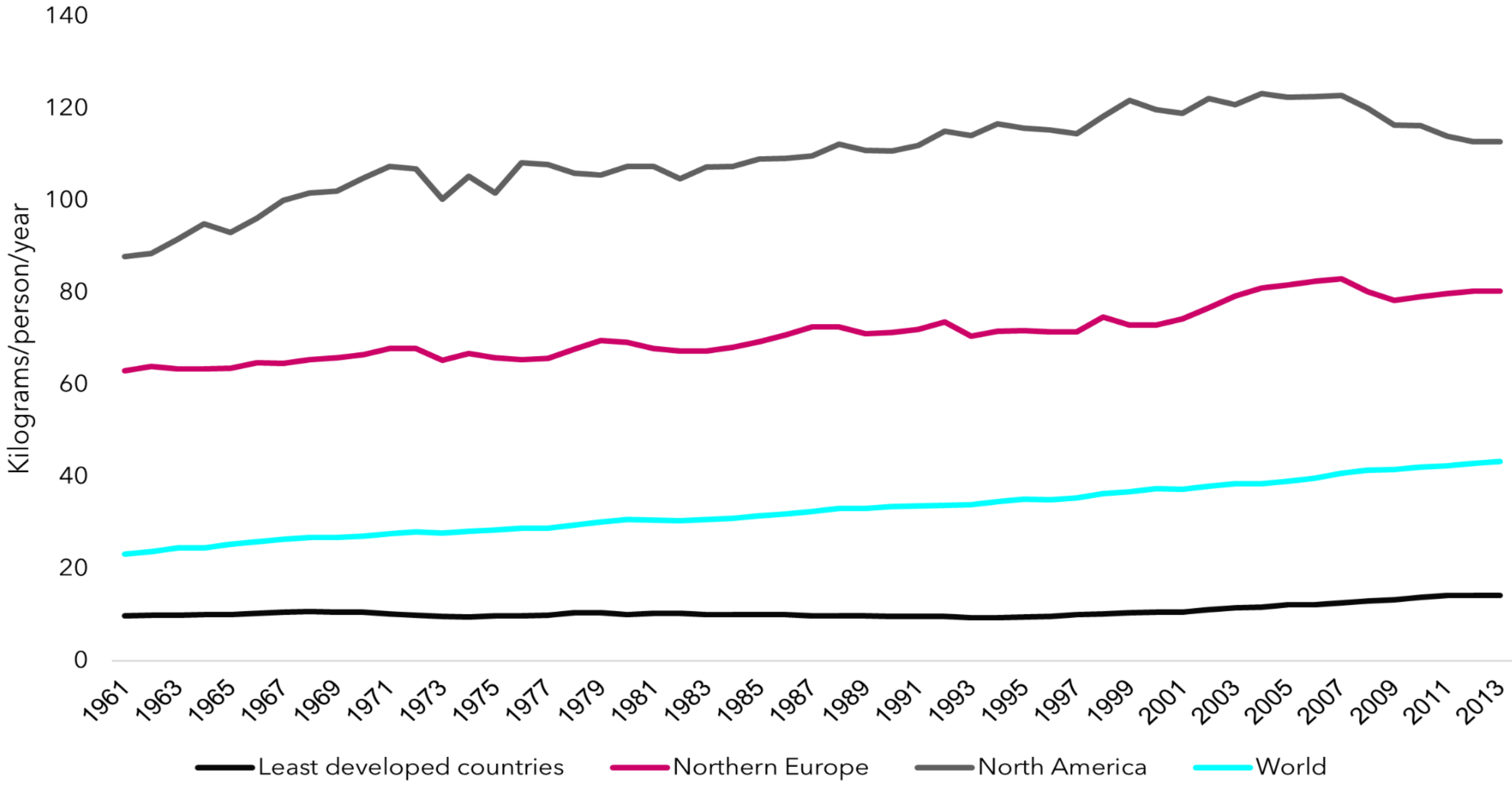

Figure 1.2. *Global per capita supply of meat (1960-2013). Source of data: Our World in Data (35).*

1.1.4 The intersection of diets, public health and climate impact

Thus far, the enhanced productivity of food systems is likely to largely have offset some of the adverse health effects from climate change and other environmental changes (36). However, the achievements in human development and health experienced over the past 70 years (section 1.1.1) may be challenged by current global diets which in several parts of the world are increasingly containing more energy-dense and processed animal foods high in sugar, and salt, but less nutrient rich foods such as fruits and vegetables (37). Driven by increasing wealth and rapid urbanization (13,38,39), imbalanced diets low in fruits, vegetables, nuts and whole grains, and high in red and processed meats, salt and refined carbohydrates, are today major contributors to ill-health globally (40). Suboptimal dietary habits contribute significantly to the prevalence of non-communicable diseases (NCDs), as well as to the global epidemic of overweight and obesity, today affecting almost a third of the global population (40,41). Dietary risks account for just over 40% of all NCD-deaths and approximately 35% of the NCD-disease burden (42). Linked to this is also a significant economic cost for health care systems (43). For example, cardiovascular disease attributed to suboptimal diets are estimated to cost approximately US$50 billion annually in the United States (44).

Overconsumption of food and especially the unprecedented demand for animal-sourced foods has pushed for the intensification of production systems with direct links to climatic impacts and health effects described here and further below (45). ***Figure 1.2*** illustrates the global per capita supply of meat over the last five decades, but also shows how the patterns of meat supply differ between regions. While these dietary and disease trends are on the rise in many population groups, roughly two billion people are nutrient deficient and over a quarter of a billion people are plausibly at the edge of starvation in areas where climate change is likely to implicate human health the most (41,46).

1.1.5 Climate change: implications for health

The increased global average temperature has resulted in the increased intensity and frequency of extreme weather events such as tropical storms, heatwaves and long-standing droughts, i.e. typical manifestations of climate change (30). Climate change is currently threatening just about every aspect of human health, something that has been thoroughly accounted for by several United Nations (UN) bodies (47,48) and scholars (6,49–51). In summary, direct health impacts from climate change include injuries, deaths and mental health problems resulting from natural disasters. Climate change also has more indirect health effects by increasing the risk of infectious diseases such as malaria, dengue fever, Lyme-disease, as well as those transmitted through unsafe food (6). It also alters the social and environmental determinants of human health such as access to clean water, sanitation, and enough, nutritious foods. These impacts may in turn generate tertiary consequences by leading to reduced worker productivity (52), human displacement (53) and even conflict (54).

Climate change further impacts the complex dynamics that determine the nutritional quality and quantity of agricultural yields. Under increased global temperatures, some areas of the world will benefit from increased crop yields, while others will not (39). This means that some countries will be forced to rely increasingly on food imports (43), challenging both national food sovereignty and equitable access to food around the world (55). Climate change will continue to negatively impact aspects such as pollination, water availability, soil quality, precipitation patterns, and temperature which all form the complex dynamics critical for food security (56). Reduced yields in some areas of the world and an progressively unpredictable food production will result in market volatilities which will increasingly threaten both food and nutrition security, especially for marginalized, low-income populations with lower purchasing power (57,58). In addition, the nutritional quality of crops is threatened by higher carbon dioxide concentrations (59,60); something likely to also disproportionally affect populations whose diets predominantly rely on staple crops of low nutrient density and who already are facing micronutrient deficiencies (55).

According to modeling studies, reduced global food availability attributed to climate change could cause more than half a million deaths worldwide by 2050 (61). A reduced access to nutrient dense foods is likely to threaten all populations, but is expected to disproportionally affect those populations that are already facing risks of nutrient deficiencies (6), thus reinforcing existing social inequities and health, wealth and wellbeing. For example, global warming of >1.5° C is estimated to drive coastal species to higher altitudes (28) which is likely to, again, disproportionally affect populations in low-resource coastal areas that depend on seafood to maintain food and nutrition security (62,63). Climate change is likely to particularly impact several determinants of child malnutrition negatively: projections show that almost five million additional children worldwide will face undernourishment in the coming 30 years under a business-as-usual scenario where climate change mitigation measures are disregarded (64).

1.1.6 Diets, climate change and ill-health in a social perspective

The relationship between the food system and Earth's systemic processes is intricate because the former both affects and is affected by the latter (65), and disruptions of both ultimately influence human health. However, not all people on the planet are equally vulnerable to climate change, and this is intrinsically linked to the level of economic wealth of a nation or a population group (66). Some population groups such as children (67), the elderly (68), and people with pre-existent disease or medical difficulties (69) will also be more vulnerable to a changing climate. Moreover, our current food systems leading to high GHGE are mainly driven by consumption patterns upheld by high-income populations, although the health consequences are predominantly affecting other populations; those having the least impactful consumption patterns which to a greater extent face climate change vulnerabilities (6). Estimations show that about 60% off the highest emitting countries globally are also the least vulnerable to future climate change (70). Conversely, acute vulnerability to climate change exists among 65% of the lowest emitting nations. Figures 1.1 and 1.2 partly illustrate this inequity, which in turn also makes climate change mitigation measures a matter of social responsibility.

1.1.7 The urgency to safeguard human and planetary health

Thus far, 196 parties to the United Nations Framework Convention on Climate Change (UNFCCC) have signed the Paris Agreement, which commits states to substantially reduce global GHGE to limit the increase in global average temperatures to well below 2, preferably to 1.5° C, compared to pre-industrial levels (71). Finding a safe operating space for feeding the projected 9-10 billion people on Earth by 2050, while ensuring that the UN 2030 Agenda for Sustainable Development (72) and the Paris Agreement (71) are attained, will necessitate unprecedented action. This includes both climate change adaptation and mitigation. The former is important but will likely not be efficient without the latter if global warming exceeds a >2° C increase; for example, changing to a more pest-resistant crop in a specific area would not make a difference if there is not enough water for the crop to grow. Recent analyses show that net-zero emission targets would likely not be met without reductions of emissions from the food system (73). With business-as-usual and no mitigation measures from the food system, GHGE are predicted to be 80-92% greater in 2050 compared to 2010 (74). It is, however, deemed feasible to mitigate climate change and its risks through various food-system solutions which will be able to promote a continuation of both economic and human development (75). A growing body of thorough scientific work has proposed climate change mitigation actions that revolve around measures such as significantly reducing global food loss and waste (6,8,56,72,73,75,76), diversifying diets and crops (6,8,56), attaining sustainable aquaculture and fisheries (6,8,56,76), achieving sustainable urban food systems (6,56), taking measures to reach replacement-level fertility rates globally through education of girls, reductions in child mortality, and increased access to sexual and reproductive health services (76), as well as achieving a sustainable intensification of agricultural production without expansion of agricultural land (6,8,56,73,76). Fundamental to climate change mitigation is also the commitment to fostering sustainable dietary habits (6,8,56,73,75,76).

1.2 PART II: SUSTAINABLE DIETS AS A PART OF THE SOLUTION

1.2.1 Sustainable diets: historical roots

As far back as 1986, Gussow and Clancy (77) discussed diet sustainability and public health. They underlined the importance of aligning both health and environmental priorities in the formulation of dietary guidelines. In 1987, their work was followed by the UN-commissioned report "Our Common Future", usually referred to as the "Brundtland report" (78). In this report, sustainable development was defined as development that "*meets the needs of the present without compromising the ability of future generations to meet their own needs*" (78). This was the first time in history where ideas of economic growth, environmental protection and social equality were united to form the basis for all development efforts, including those connected to food. More than two decades later, the first official intergovernmental attempt to address diet sustainability was made at a scientific conference in Rome, Italy, led by the Food and Agricultural Organization of the United Nations (FAO). Here, a broader definition of the notion was formulated:

> *"Sustainable Diets are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources"* (79).

In the following year, a similar but slightly more dynamic conceptualization was suggested by the United Kingdom's Sustainable Development Commission. The commission proposed a framework based on six dimensions of food sustainability; Quality, Social values, Environment, Health, Economy, and Governance (80). According to Mason and Lang (81), this framework offers useful values through which diets could be holistically addressed from a policy perspective. Another recent attempt to define sustainable diets was undertaken by the FAO jointly with the World Health Organization (WHO) in 2019 (82). Here, 16 guiding principles for sustainable and healthy diets were established to emphasize the role of food consumption and diets in contributing to reaching the SDGs at national level. However, these principles are communicated mainly as qualitative recommendations and may not be specific enough for the quantification and assessment of sustainable diets (55).

1.2.2 Links to present global sustainability targets

Today, the notion of diet sustainability is a central part of international policy. Critical for reaching the 1.5° C target of the Paris Agreement (71), it also permeates the UN 2030 Agenda for Sustainable Development, with its 17 goals (72), of which more than half can be considered inextricably linked to the sustainability of diets, as summarized in **Table 1.1**. Hence, diet sustainability appears to be critical for achieving *"peace and prosperity for people and the planet, now and into the future"* (72). Considering its central role to global health and development, increasing efforts to define sustainable diets scientifically can now be found in literature.

Table 1.1. *Links between the UN Sustainable Development Goals and diet sustainability.*

Sustainable Development Goal (of 17 in total)	The current unsustainability of diets and food systems…
1. No poverty	disproportionally affects vulnerable populations and without action the effects of an unstable Earth system will counteract this goal e.g., through forced migration and loss of livelihoods
2. Zero hunger	causes environmental change posing imminent threats to food and nutrition security
3. Good health and wellbeing	is a major cause of ill-health
6. Clean water and sanitation	consumes a major part of global fresh water thus compromising access to clean water and sanitation
10. Reduced inequality	contributes to ill-health and environmental adversities, disproportionally affecting low-resource populations
12. Responsible consumption and production	is currently not responsible as it threatens both human and planetary health
13. Climate action	is one of the main drivers of climate change
14. Life beyond water	contributes to the acidification of oceans and aquatic biodiversity loss
15. Life on land	drives deforestation and terrestrial biodiversity loss
16. Peace justice and strong institutions	is a result and a driver of conflict

1.2.3 Estimating environmental and health impacts of foods and diets

1.2.3.1 Life Cycle Assessment of foods

Life Cycle Assessment (LCA) is an analytical- and decision support-tool for quantifying the environmental impact of food production and processing (83,84). The LCA of foods (**Figure 1.3**) essentially encompasses the impacts of a product from extraction of raw materials (e.g. coal), through factory production, distribution, usage and ultimately also final waste management (85). What characterizes climate and other environmental impacts from food compared to other products is that primary production, and its inflows and activities (feed, animal husbandry, production of mineral fertilizers, emissions from fertilizers and animals), often represents the main part of the product's total climate impact (85,86).

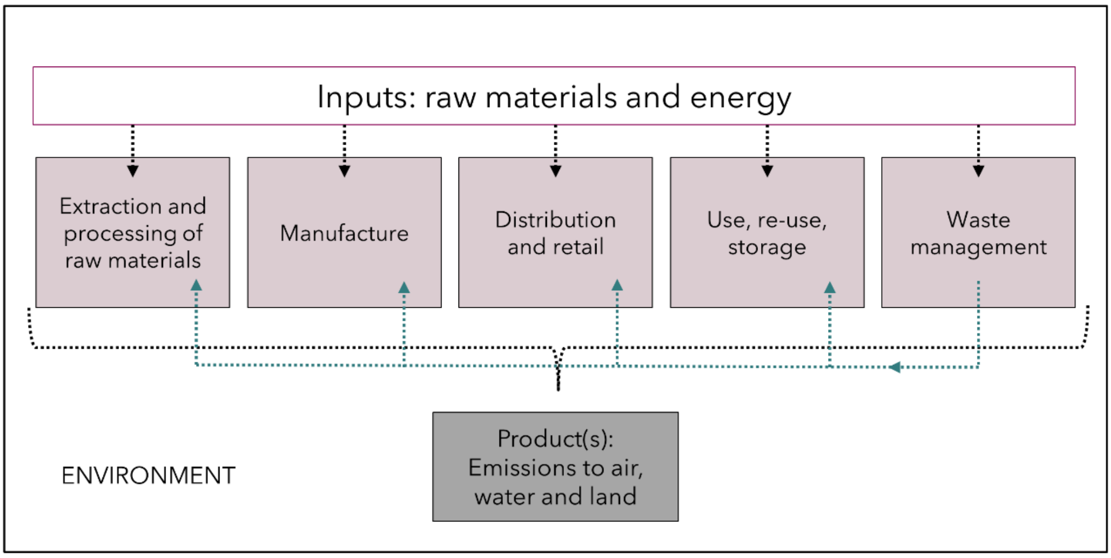

Figure 1.3. *Flow of life cycle thinking (Adapted from McLaren S.J. 2010 (85)).*

It is difficult to determine the precise environmental impact of different foods due to the lack of consistent, reliable and comprehensive data for all environmental impact dimensions (87). Hence, most available data are based on LCA-data of the climate footprint (i.e. GHGE) of different foods (87). Despite the large underrepresentation of other environmental impact domains in food footprint LCAs, there seems to be a clear pattern for the impact of foods when aggregated into larger categories. For example, a recent consolidation of LCA-data of 40 agricultural goods from 38,000 farms globally showed that even the lowest-impact animal products have higher impacts than substitute vegetable proteins across several environmental impact categories, including GHGE (86). Furthermore, a systematic review of 369 LCA studies showed that ruminant meat had the largest carbon footprint per serving, while cereals, fruits and vegetables had the lowest (88).

1.2.3.2 Environmental impacts and health effects of different diets

The last decade has presented a growing body of literature reviewing the environmental impact of different diets (87,89–93). Firstly, the mere adoption of an energy balanced diet could potentially reduce diet-related GHGE by up to ~20% (87,91,93,94). Moreover, evidence consistently indicates that reductions in the amount of animal foods in the diet go hand in hand with reductions in the environmental impact of the diet (87,89–91,93). For example, Hallström et al. (93) showed that reductions by up to 50% in both GHGE and land use were achievable by shifting from meat-based to vegetarian or vegan diets. Nevertheless, some plant-based dietary scenarios were found to have similar or higher environmental footprints as animal-based diets when expressed per calorie. The functional unit used to compare foods may thus play an important role in diet sustainability assessments. For example, fruits and vegetables were the lowest GHGE when measured per 100 g, but had impacts close to that of pork, poultry and eggs when instead assessed per 100 kcal (95). Similarly, Masset et al. (96) found that foods lower in GHGE were of lower cost and higher nutritional profiles when assessed per 100 g. However, when assessed per 100 kcal the same foods were of lower cost but less nutritious.

Authors have also synthesized potential health effects from diets of lower environmental impacts. A review by Nelson et al. (91) identified an overall health benefit in both cross-sectional as well as modeling studies assessing diets higher in plant-based foods and lower in animal products. In contrast, a review of modeling studies did not observe significant mortality-risk reductions from similar dietary patterns (90). Moreover, Payne et al. (92) found that reduced GHGE of diets were associated with lower micronutrient intakes and higher intakes of foods rich in refined sugars. Similarly, Swedish self-selected diets with the lowest GHGE have been shown to align worse with recommendations for added sugars compared to diets with the highest GHGE (97).

The EAT Lancet Commission Report (8) presents the most recent and comprehensive research to highlight synergies between healthy diets and sustainability with regards to the six key Earth system processes mentioned previously (section 1.1.2). The report proposes a global healthy reference diet with potential to both improve health outcomes and safeguard environmental sustainability. For most high-income populations, adoption of such a diet would imply increasing consumption of plant-based foods significantly while markedly reducing consumption of animal-based products (98). However, the extent to which dietary shifts would result in synergistic health and environmental benefits is likely to be context dependent. Diets in low-income settings are still predominantly plant-based (46). In these settings, where access to a diversity of foods is limited, animal products can contribute with essential nutrients important for survival, especially for children (99). Such populations would most likely experience health benefits from following a global healthy reference diet, yet, environmental impacts from their diets would likely also increase (98). Conclusions drawn in much of the current literature on diet sustainability might therefore not be relevant or meaningful for low-income settings (100). In summary, these findings highlight some of the complexities in defining a sustainable diet and emphasize the centrality of considering context in research of this field.

1.2.3.3 The need for holistic approaches

Additional dimensions of diet sustainability might also deserve attention. For example, it is estimated that the cost of the healthy EAT-Lancet diet would exceed the household budget of more than 1.5 billion people globally (101). Moreover, studies have shown that self-selected diets with a higher nutritional quality are associated with higher GHGE (102,103) and higher cost (104). This indicates that dimensions of diet sustainability may not always be compatible or synergistic (89). To better understand these dynamics, contemporary sustainable diets might need to be explored and established using holistic approaches (89,90,93,100) where human and planetary health needs are considered alongside with economic, social and cultural priorities. One assessment method that has been judged suitable for simultaneously exploring multiple criteria, such as those of sustainable diets, and for mathematically identifying potential trade-offs is optimization with linear and non-linear programming (105,106).

1.2.4 Optimizing diets for sustainability and acceptability

The optimization of diets can be dated back to World War II when mathematicians were hired to calculate the composition of low-cost and nutritionally adequate diets for American soldiers. In 1947 George Dantzig became the first mathematician to succeeded in establishing the right combination of foods for effectuating a nutritionally adequate diet at the lowest possible cost (107). This problem was solved by using the optimization method linear programming (LP). Linear programming is the application of an algorithm for maximizing or minimizing a given (linear) objective function subjected to a set of (linear) constraints on a list of decision variables (108). These three parameters constitute the optimization model. Diet optimization models aim to arrive at the optimal combination of foods for attaining the minimum or maximum of a linear objective (e.g. GHGE), while at the same time fulfilling a set of constraints (e.g. cost, nutrient reference values, food based dietary guidelines).

Since Dantzig, researchers have applied different optimization techniques to model more affordable, healthier and/or more environmentally sustainable diets to guide policy development (105,106,109–111). Large reductions in different environmental metrics compared to current diets have been achieved with LP (110,112,113). However, these diets have also deviated substantially from current ones. Therefore, appropriate knowledge on how to address the acceptability in the modeling of new diets has been highlighted as key to avoid e.g. a reduced consumption or an increased food waste (106).

Diet acceptability (DA) as a concept has been increasingly invoked as an important constituent of optimization studies aiming to propose new diets that also are acceptable to consumers. Researchers have used many different strategies to mathematically operationalize this concept (110,112–154) and the characteristics of the ones reviewed for this thesis are presented in Supplementary Table 1. All reviewed studies covered nutritional aspects of diets. Around 70% (112,114,116–120,122–125,128–130,132–137,139,140,143,144,146,148–153) applied DA into their optimizations by minimizing the departure from current dietary patterns. The rest minimized either diet cost or an environmental impact category (e.g. GHGE) and instead included different constraints to mathematically operationalize DA. Slightly more than half of all studies (110,112–116,121,124,127,129,136,139–142,145,147–150,152–154) considered one or several environmental aspects of diets in the model, and approximately half of these (110,112–114,121,124,136,140–142,149,154) additionally considered the affordability of the modeled diet.

Most of the studies that minimized the departure from current dietary patterns also applied additional DA constraints to their optimizations. For example, Chaudhari and Krishna (117) constrained their models so that the optimized amount of a particular food item could not exceed or fall below pre-defined consumption levels of the observed populations. Furthermore, food items that were not consumed in a country due to cultural, religious or availability reasons were restricted from inclusion in the model. Also, the total mass (weight) of the optimized diet was constrained to stay between ±20% of the levels in the current diet. A similar approach was taken by Vieux et al. (152) and Perignon et al. (112), who limited the total mass of the diet as well as constrained food item, food group and food subgroup amounts to the 90th percentile of current intake levels. In another study (120) the energy-contribution of each major food group was constrained to stay between the 5th and 95th percentiles of baseline values, besides making sure that portion sizes for each food were constrained by an upper limit. Darmon et al. (119) applied the same portion-size constraints but had a more relaxed constraint on the energy-contribution of each major food group (10th and 90th percentiles of baseline values). As in previously mentioned papers (119,120), researchers in India (140) also adjusted their models in terms of constraining the energy-contribution of each major food group. Furthermore, certain miscellaneous food items were held constant in this study. The relative deviation of food items within food groups were also constrained to increase by a maximum of 100% and reduce by a maximum of 90% in order to enhance the DA of the optimized solutions. Other researchers (125,137) constrained their models by limiting the weight of each food within their specific food group to a maximum level in order to achieve dietary diversity. While being less usual, food- or food group-ratio constraints have also been applied by some researchers (113,126,144,146,152). For example, Henson (126) applied 52 palatability constraints where portion-ratios between different food groups were constrained to the ratio in which they were usually consumed, while Vieux et al. (152) constrained the ratio of solid-to-liquid food weights to match the observed intake.

Based on this growing body of research, the minimization of the deviation from present consumption patterns and applying DA constraints to the model in various ways seems to be a preferred strategy for achieving culturally acceptable diets that are nutritionally adequate, affordable and/or environmentally friendly. This approach specifically highlights how environmental priorities and current diet preferences, both equally important to consider, set the scene for what contemporary sustainable diets could look like. However, to fully understand levers of dietary change, research needs to move beyond the mathematical operationalization of sustainable diets to also understanding how to best foster their adoption by consumers (87). In this regard, taxes and subsidies, focused marketing on sustainable foods, nudging (i.e. measures to promote specific decisions without limiting choices), and restriction of unsustainable products are some of the suggested measures for encouraging the consumption of low-GHG emitting and healthy foods (8,59,155). The public sector has also been proposed as a suitable and underutilized setting in which sustainable diets could be fostered in practice (8,155,156).

1.2.5 The role of the public sector in achieving dietary shifts

As concluded by the European Live Well for Life project, consumers can be guided towards more sustainable consumption patterns by green public procurement policies (157). Of the total consumption-based emissions of GHG in Sweden (82 million tons in 2018), about 11% can be attributed to public sector consumption, i.e. the goods and services that e.g. schools, hospitals and local authorities purchase in order to conduct their operations (158). A share of these emissions result from public procurement of food. Today about 3 million meals are being served daily in the Swedish public sector. Sustainable public procurement of food in Sweden thus hold substantial potential to contribute to climate change mitigation (155). Awareness of, and access to, sustainable foods could contribute to norm-shifts around diets at a societal level. These particular aspects may be especially relevant for children, who are predominantly reliant on the foods available at home and at school (156).

1.2.6 The potential of school meals to foster both healthy and climate friendly diets

1.2.6.1 School meals and healthy diets

In high-income contexts, low socioeconomic status (SES) is positively associated with an increased risk of chronic diseases (159,160). This association can to some extent be explained by a lower diet quality (161,162). School meals—particularly when free of charge or heavily subsidized—can reach school-aged children of every socioeconomic background (163). These meals thus provide a near unique opportunity for all children to establish healthy dietary habits early in life; something that is key to promoting public health (163). School lunches have been shown to be effective in terms of encouraging the intake of nutritious foods such as fruits, vegetables and fish compared to packed lunches brought from home (164,165). Moreover, school meals can constitute a significant share of children's dietary intake over a considerable and critical period of life (156) when long-lasting dietary habits are shaped (166–168). They therefore hold substantial potential to promote healthy dietary habits in children of every socioeconomic background and thereby narrowing long-term social health inequalities (169,170).

The features of school meal services vary extensively across the world; in many high-income countries this service is generally available for free or at a reduced cost to parents (169). Sweden introduced publicly financed school meals in the late 1940s (171). The country is currently unique in providing lunches to all primary school children (up to the age of 16) as well as to most secondary school pupils aged 16-19. These meals are provided free of charge to parents, regardless of family income (172). Today, 1.1 million fully subsidized lunches, typically consisting of one or more hot main dishes, a salad buffet as well as bread and spread, are served daily to all Swedish primary school children (173). This amounts to approximately 200 million lunches per year that are served in all of the country's almost 5000 primary schools at a total cost (including food, personnel and transportation) of about 7 billion Swedish krona (~700,000 million EUR) (164). These meals are usually planned centrally in the municipality and are intended to cover 30% of children's daily dietary intake (174). As of 2011, Swedish law specifically states that school meals must be nutritious (175). However, knowledge about children's dietary intake from school lunches is scarce. The latest relevant evaluation was made on dietary data collected in 2003 and showed that children in grades 2 and 5 had inadequate intakes of several nutrients compared to reference values used for meal planning (174). Research covering school lunch intake from children in older grades across sex and socioeconomic groups is also limited.

In 2016-17, the Swedish Food Agency performed a national dietary intake survey among primary school children and adolescents (176). This data presents an opportunity to gain new insight into the role that school meals play in Swedish children's diets, but also to understanding the potential of these meals in promoting healthy dietary habits in an equitable manner.

1.2.6.2 School meals and climate friendly diets

Meals provided in school hold potential to also foster climate friendly eating habits in children. Children's diets are affected by many sociocultural factors, including the home (177) and school environment (178). For example. eating a balanced school lunch has been shown to impact eating patterns outside school (179). Furthermore, schools provide learning environments around food (156) that could facilitate the implementation of optimal diet-solutions in real world settings. The exposure to, and consumption of, school meals over a considerable period of childhood is thus likely to be an important arena for children to internalize sustainable dietary patterns, which may persist throughout life (166–168).

Opportunities to promote diet sustainability in the school meal setting exist, but acceptability by students has to be considered while also meeting nutritional and cost priorities. Many schools and public sector meal planners in Swedish municipalities are today making dedicated attempts to achieve more climate friendly menus by heuristic techniques. However, the process is labor-intensive, requiring many iterations which do not always guarantee fulfilment of requirements regarding nutritional adequacy, cost, and food acceptability. Holistic approaches that simultaneously ensure the climate friendliness, nutritional adequacy, affordability and acceptability of school meals would thus be valuable to avoid potential unintended effects. Such approaches hold substantial potential to contribute to more sustainable procurement and consumption patterns, a more efficient use of public resources, an improved public health, and ultimately contribute to the fulfilment of both national (180) and international (71,72) commitments for climate change mitigation.

2 RESEARCH AIMS

The overall aim of this doctoral thesis is to contribute to knowledge of how sustainable dietary habits could be achieved through the school meal system in theory and practice. More specifically, this thesis aims to:

I. Study what children eat during school lunch and how their school lunch intake contributes to overall dietary intake in different age and socioeconomic groups.

II. Develop a holistic linear optimization strategy for achieving a GHGE-reduced, nutritionally adequate, affordable and acceptable—i.e. sustainable—Swedish school food supply.

III. Explore if the strategy developed can be combined with meal planning in practice to achieve a new sustainable school lunch menu and study if the introduction of the new menu affects food waste, pupils' food consumption as well as their satisfaction with the meals.

IV. Explore how pupils and kitchen staff experienced the introduction of the new menu and identify barriers and facilitators to successful implementation of sustainable school meals.

To achieve these aims, four studies (Study I-IV, reproduced in full in Appendix I-IV), have been carried out. **Figure 2.1** provides an overview of the four studies and show how they build upon one another.

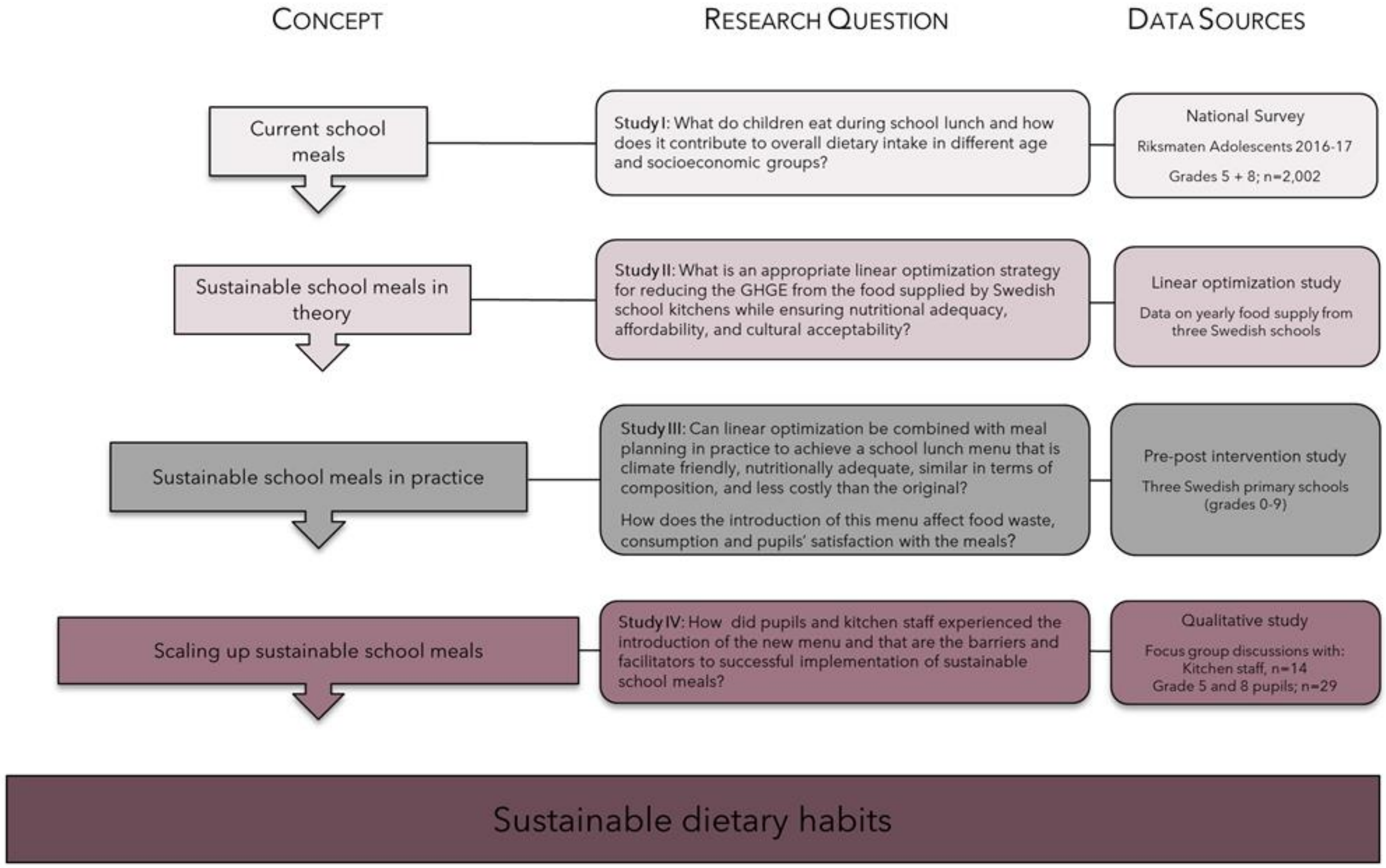

Figure 2.1. *Overview of doctoral thesis showing how Study I-IV build upon one another. GHGE, greenhouse gas emissions.*

3 MATERIALS AND METHODS

3.1 RIKSMATEN ADOLESCENTS 2016-2017 – A NATIONAL DIETARY SURVEY (STUDY I)

Study I uses data from Riksmaten Adolescents 2016–2017, the second national dietary survey performed on Swedish children and the first ever to include adolescents (176). This school-based survey was carried out by the Swedish Food Agency between September 2016 and May 2017 in school grades 5 (ages 11-12 years) 8 (ages 14-15 years), and 11 (ages 17-18 years). Dietary intake was self-reported through the validated web-based dietary assessment method RiksmatenFlex (181), and other relevant information (e.g. background characteristics and self-reported physical activity) was collected through web-questionnaires. Pupils' weights and heights were measured by trained field assistants from the Swedish Food Agency, who also gathered blood and urine samples from pupils in a randomly selected sub-sample (40%) of schools (176).

Recruitment of pupils was performed on school level (176). Statistics Sweden first selected approximately 200 schools from each school grade (in total ~600 schools) to provide a nationally representative sample for the survey. These schools were sampled with regards to municipality type, type of school (publicly/privately managed), and geographical spread. Schools having few pupils (<10) in the grades of interest, or schools only providing langue introduction classes were excluded. Principals in 601 schools were invited to participate in the survey. From these, 131 (22%) agreed participation, resulting in a sample of 5,145 invited pupils of which 58% (n=2,968) had complete diet information for all three intended recall days.

Ethical approval for the survey was obtained from the Regional Ethical Review Board in Uppsala (No. 2015/190). Legal guardians of all pupils in the participating schools were provided with an information letter regarding the survey, and written informed consent was obtained from pupils or legal guardians of pupils below the age of 16 that were going to provide biological samples. In other cases, opt-out consent was approved by the Ethical Review Board.

3.1.1 Reported dietary intakes with RiksmatenFlex

RiksmatenFlex is a web-based dietary assessment tool developed by the Swedish Food Agency for the Riksmaten Adolescents 2016-2017-survey (181). This tool consists of two components: questionnaires (RiksmatenFlexQ), and a dietary registration (RiksmatenFlexDiet). The latter is based on repeated 24-hour multiple pass recalls and has been validated against 24-h recall interviews and biomarkers (181). Pupils taking part in the survey registered the types and amounts of all foods and drinks consumed during two consecutive days and ideally also for one additional (non-consecutive) day (176). On the day of the school visit, pupils retrospectively reported their dietary intake from the previous day as a 24-hour recall (Day 1). This was done in the classroom, with support from the trained field staff from the Swedish Food Agency. They then continued to record their dietary intake prospectively during the day of the school visit (Day 2). A third day—randomly assigned four to ten days after the first day—was recorded retrospectively as a 24-hour recall (Day 3).

The food list of the dietary registration consisted of 778 foods directly linked to the Swedish Food Agency's food composition database, version *Riksmaten Adolescents 2016–2017*. Energy and nutrient intakes could thus be automatically calculated for each pupil. The tool provided visual aids such as a picture portion guides, household measures and conventional amounts (such as slices) to facilitate pupils' estimation of their intake of different food/drinks. Pupils were asked to indicate the time, type and location (home, school, restaurant etc.) of the consumed meal. Automatic messages were provided to remind pupils about commonly forgotten foods, and they were prompted to double-check the accurateness of their food-reports before completing each registration day.

RiksmatenFlexQ contained different questionnaires, one of which was directed to the pupils' parents. Here, parents reported their highest level of education attained. Birth country of the pupil and parents was reported by the pupils themselves in another questionnaire. Information on sex, age and school grade was made available to Swedish Food Agency-staff before the school visit.

3.1.2 The dietary intake of grade 5 and 8 pupils

Study I focused on the 2,002 pupils in grade 5 (n=990) and grade 8 (n=1,012). Pupils in grade 11 (n=966) were not included as they are not covered by the free meal entitlement in Sweden. Since the aim was to only explore school meal contribution to children's overall diets, intakes on non-school days (n=1,241) were excluded. Furthermore, days where the school lunch was consumed outside the school premises (n=667) were also excluded. The analyses thus assessed a final number of 4,098 dietary days **Figure 3.1**.

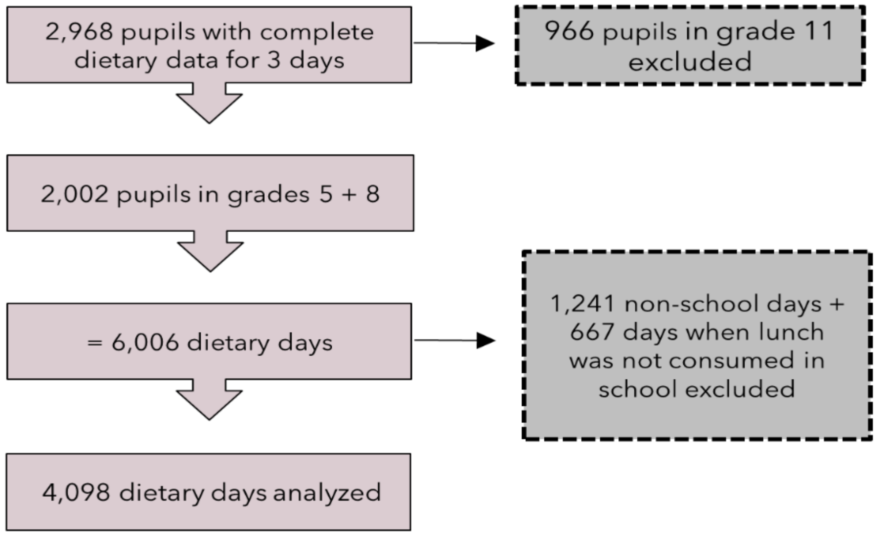

***Figure 3.1**. Flow diagram for selection of pupils and dietary days.*

3.1.3 Dietary reference values (DRVs)

The Nordic Nutrition Recommendations 2012 (NNR) constitute the official nutritional recommendations in Sweden (182) and include dietary reference values (DRVs) (182) for energy and nutrients. These DRVs include; *Average requirement* (AR), intake level covering the dietary needs of 50% of a population group; *Recommended intake* (RI), intake level covering the dietary needs of ~97-98% of a population group; *Lowest intake level* (LI), the level of intake below which a majority of individuals are likely to experience clinical deficiency symptoms; *Upper level of intake* (UL), the maximum daily intake of a nutrient which is not likely to generate adverse health effects in healthy population groups, *Estimated energy requirement (EER*), and; *Recommended intake range of macronutrients*, based on health benefits/risks of macronutrient intakes.

The DRVs defined in the NNR constitute the basis for the Swedish Food Agency's general food based dietary guidelines (FBDGs) (183) as well as for the Swedish school meal standards (174). These standards are used for planning of school meals, which since 2011, are required to be nutritionally adequate by law (175). According to the Swedish school meal standards (174), an average school lunch should provide 30% of selected daily DRVs (relevant for school-aged children, boys and girls) over a longer continuous period of time. These standards do currently not provide ARs for school meals. In Study I, pupils' average school lunch intake of energy, vitamin D, iron, folate, fiber and saturated fat was therefore compared against the EERs and RIs indicated in the standards.

3.1.4 Calculating intakes of energy, nutrients and food groups

This paper assessed pupils’ intakes of energy, vitamin D, iron, folate, fiber, saturated fat as well as the food groups vegetables, fish and red/processed meat (**Figure 3.2**). The reason for selecting energy, vitamin D, iron, folate, fiber, and saturated fat was primarily to enable a comparison with previous research (184), which found that pupils’ intake of these dietary components from the school lunch was not in line with the DRVs in the Swedish school meal standards. The food groups were selected as they constitute key components of the Swedish FBDGs (183). Pupils’ consumption of vegetables, fish and red/processed meat included both amounts consumed as discrete items (e.g. a carrot) and estimated amounts from consumption of composite dishes (e.g. carrots in a stew).

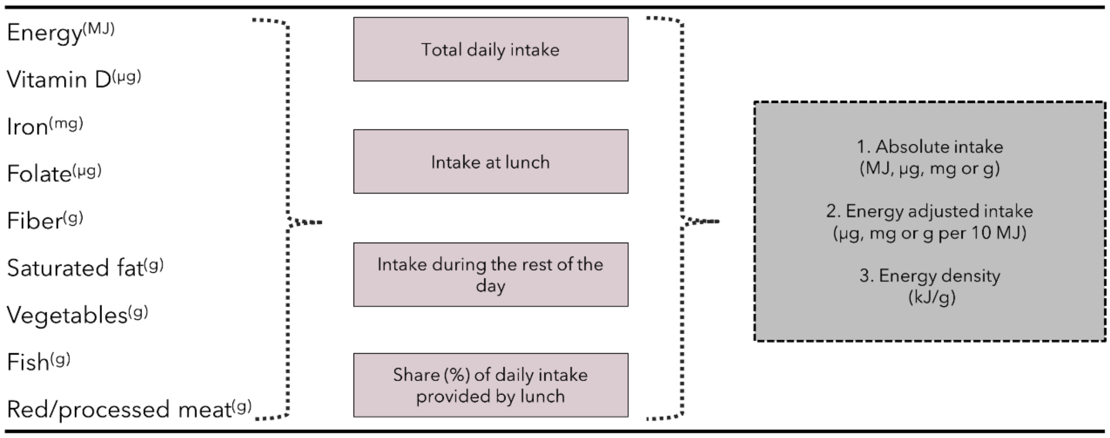

Figure 3.2. *Parameters of pupils’ dietary intake that were assessed.*

For the purpose of Study I, total (overall) daily intake, mean intake at (school) lunch and mean intake excluding lunch (i.e. intake during the rest of the day) was calculated for each of the 2,002 pupils (Figure 3.2). The share (%) of the total daily intake that was covered by the school lunch was also quantified. Furthermore, pupils’ absolute intakes of energy and nutrients from school lunches by sex and school grade were compared against the DRVs in the Swedish school meal standards. This was done to obtain a sense of how well pupils’ intakes are in line with the planned meals.

Amounts of nutrients and food groups were calculated in µg, mg or g as well as adjusted for energy intake (µg, mg or g per 10 MJ). Energy intake (MJ) and the energy density (kJ/g) were also quantified; the latter known to be an indicator of diet quality in Swedish adolescents (185). Energy density was calculated by dividing the total energy intake from food (including soups and yoghurt but excluding drinks) by the total weight of food (185,186).

3.1.5 Considering sociodemographic characteristics

The sociodemographic variables used to describe and/or analyze the study sample are summarized in **Table 3.1.** Overweight and obesity was determined on the basis of height and weight measurements taken by the Swedish Food Agency's field staff using standardized methods (187) and calibrated equipment. The International Obesity Task Force body mass index (BMI) cut-offs for children were applied for this categorization (188). Area of residence was assigned to pupils based on information from Statistics Sweden. This variable was categorized as urban, semi-urban, or rural (176).

Table 3.1. Sociodemographic characteristics that were considered for descriptive and/or analytical purposes.

Variable	Data source	Categorization
Sex	Provided by school administration prior to school visit	Male, Female
School grade	Provided by school administration prior to school visit	Grade 5, Grade 8
Age	Provided by school administration prior to school visit	na
Parental education	Provided by parents through questionnaire in RiksmatenFlexQ	≤12 years = low parental education >12 years = high parental education
Birth country	Provided by pupils through questionnaire in RiksmatenFlexQ	Pupil and at least one parent born in one of the Nordic countries OR Pupil born outside of Nordic countries* but both parents Nordic-born = Nordic All other cases = Non-Nordic
Overweight status	Height and weight measured by the Swedish Food Agency's field staff during school visit	BMI ≤25 = normal weight BMI >25 overweight/obese
Area of residence	Provided by Statistics Sweden	Urban = large cities/municipalities close to large cities Semi-urban = larger cities/municipalities close to larger cities Rural = smaller cities/densely populated areas

*Sweden, Finland, Norway, Denmark, or Iceland.

3.1.6 Statistical analyses of pupils' dietary intake

Descriptive statistics of pupils' dietary intake were computed and presented as means with 95 % confidence intervals (CIs) or standard deviations (SDs). The significance level for all inferential analyses was set at <0.05. Pupils' energy-adjusted intakes of nutrients and food groups and the energy density of their dietary intake (at lunch vs. the rest of the day) was assessed by applying mixed-effects linear regression models (189). Mixed-effects linear regression analyses were also performed to investigate differences in pupils' dietary intake of energy, nutrients and food groups by sex and level of parental education.

Three different sets of models were set up to investigate differences in the three different outcomes (Y):

Model 1: Y = Total daily intake of energy, nutrients and food groups (energy adjusted)
Model 2: Y = Intake of energy, nutrients and food groups at lunch (energy adjusted)
Model 3: Y = Share (%) of daily intake of energy, nutrients and food groups provided by lunch

Each of the three models included the sociodemographic variables sex, grade and parental education as independent fixed effects and the primary sampling unit (school) as an independent random effect. Pupils' intake during the rest of the school day was included as an independent fixed effect when comparing pupils' dietary intake at lunch. This was done to adjust for the plausible variation in pupils' dietary intake at lunch explained by pupils' dietary intake during the rest of the day.

3.2 DEVELOPING AN OPTIMIZATION STRATEGY FOR SWEDISH SCHOOL FOOD SUPPLIES (STUDY II)

For the optimization modeling performed in Study II, data on the annual school food supply of three Swedish primary schools (grades 0-9) from three different municipalities were used. The data contained listed information on approximately 2000 food/drinks that had been purchased by each school over the school year 2015/2016. The data also included information on the purchased amount (in kilograms), their price per kilogram, as well as the total cost (kilogram*price per kilogram) of each purchased food/drink. The weight of foods/drinks that had been bought at multiple occasions over the school year in each school were aggregated to obtain condensed food lists (one for each school) of compositionally distinct food items.

3.2.1 Estimating cost, nutrient content, and climate impact of the school food supply

3.2.1.1 Cost of foods

Since the price of the same compositionally distinct food varied over the school year, each aggregated food item was assigned a weighted average price per kilogram. This value was calculated based on the average price per kilogram of a food when it was purchased, weighted by the amount ordered.

3.2.1.2 Nutrient content of foods

All foods/drinks in the observed school food supply were manually matched with their corresponding nutritional content as reported in the Swedish Food Agency's food composition database, version 20170314. Here, the nutritional values of foods as eaten (e.g. cooked spaghetti) as well as of foods in their raw form (dry spaghetti) were extracted. The former was needed for estimations of nutritional adequacy, i.e. nutrient content of the food supply in its edible form. The latter was needed to estimate actual raw weights of the optimized food supply, i.e. the amount of raw food that was needed to cover the nutritional demands for a school lunch. Edible proportions, as provided by the food composition database, were also applied to convert amounts of purchased raw foods into amounts of edible foods.

3.2.1.3 Climate impact of foods

Information on the climate impact of different foods was extracted from the Climate Database provided by the Research Institutes of Sweden (RISE). The version of the database used in Study II contained 2,078 foods and could automatically be linked to the Swedish Food Agency's food composition database through shared ID-numbers for all individual foods. The Climate Database contains information on the climate impact of foods which in turn build on results from LCA (83,84)**.** The climate impact of different foods in the database is expressed as CO_2eq, i.e. the combined measure of the GHG carbon dioxide, methane, and nitrous oxide. The Climate Database builds on the GHG-weighting factors reported in the 2007 IPCC-report (190). Here, carbon dioxide, methane and nitrous oxide were assigned the GWP_{100} weighting factors 1, 25 and 298, respectively. The climate impacts of foods in the database have also been weighted according to Swedish food supply patterns (191). Hence, differences according to production systems, origin, assumed mode of transportation and consumption are to some extent considered.

The functional unit in the climate database is kg CO_2eq/kg food product and the system boundaries for calculating the CO_2eq values is from primary production until the factory gate and exclude packaging. The CO_2eq of the last three stages of the LCA (**Figure 1.3**) have not been accounted for. As a result, the climate impact from food preparation (impacts from energy use) is not included. For imported food, a general transport to Sweden is included. The data in the RISE Climate Database are based on LCA/climate calculations performed by RISE or other national and international actors as well as on scientific articles, publications from conferences, popular science reports, environmental/climate declarations, international climate labelling initiatives or on simplified calculations/modifications based on RISE's collective experience in the area of food and climate impact.

3.2.2 Optimization

3.2.2.1 Linear programming (LP)

Linear programming (LP) is the application of an algorithm for either maximizing or minimizing a given linear objective function (the variable to be optimized) which is subjected to a set of linear constraints (conditions to be met) on a list of decision variables (108). These three parameters constitute the optimization model. Diet optimization models aim to arrive at the optimal combination of foods for attaining the minimum or maximum of a linear objective (e.g. GHGE), while at the same time fulfilling a set of constraints (e.g. cost, nutrient reference values, food based dietary guidelines). The foods (whose amounts are to be changed by the LP-algorithm) usually constitute the decision variables. A feasible solution is found when all constraints can be met.

3.2.2.2 The observed food supply for one reference pupil and day

For modeling purposes, the observed food supply for one pupil and day was calculated on the basis of the EER in the Swedish school meal standards (174). According to these recommendations, a reference school lunch should on average provide 604 kcal per day and reference pupil if assuming a school with an equal distribution of females and males, as well as an equal number of pupils in each of the 10 primary school age categories (7–16 years). This reference value (604 kcal), together with the total amount of kcal for all foods reported as purchased, was used to calculate a daily energy-standardized food supply of each food item for one pupil. The daily energy-proportional shares of each food for one pupil were calculated for modeling purposes and represented the observed food consumption.

3.2.2.3 Deviation from the observed food supply for one reference pupil and day

In order to be able to assess the similarity between the observed and the optimized food supply, different indicators of the deviation from the observed food supply (i.e. a proxy DA) were calculated for one reference pupil and day (**Table 3.2**).

Table 3.2. Different indicators of the deviation from the observed food supply with formulas and descriptions.

Measure of deviation	Formula	Description
Relative deviation (RD)	$RD_i = \frac{(M_i - m_i)}{m_i}$	Relative (%) deviation for individual foods in the optimized food supply in relation to the observed food supply. Here, m_i stands for the observed supply of the i-th food item in grams provided to the reference pupil and M_i is the weight of the i-th food item after optimization
Total relative deviation (TRD)	$TRD = \sum_{i=1}^{N} abs(RD_i)$	The total sum of the absolute values of RDs
Average relative deviation (ARD)	$ARD = TRD/N$	TRD divided by the total number of food items included in the model
Relative ratio deviation (RRD)	$RRD_j = \frac{(R_j - r_j)}{r_j}$	Relative (%) deviation for food group ratios in the optimized food supply in relation to the observed food supply. Here r_j stands for the observed supply of the j-th food-group and R_j is the supply of the same food group after optimization
Total relative ratio deviation (TRRD)	$TRRD = \sum_{i=1}^{N} abs(RRD_i)$	The total sum of the absolute values of RRDs
Average relative ratio deviation (ARRD)	$ARRD = \frac{(\sum_{j=1}^{N} abs(RRD_j))}{M}$	TRRD divided by the total number of food group ratios included in the model

3.2.3 Modeled pathways

To find an appropriate LP-strategy for reducing the GHGE of the Swedish school food supply while ensuring its nutritional adequacy, affordability, and DA, Study II identified pathways focusing on two different approaches dominating the scientific literature in the area of the diet optimizations: 1) whether diet-related GHGE should be minimized to achieve a food supply with a minimal climate impact, or 2) whether the deviation from prevailing food supplies should be minimized to achieve a food supply with a minimal deviation from observed supplies.

Based on these approaches, four possible pathways for the optimization of the school food supply were developed (**Figure 3.3**). To achieve a school food supply with a minimum climate impact, total food related CO_2eq (i.e. GHGE) were first minimized in Model 1. For Models 2-4, the minimization of the total relative deviation (TRD) from the observed school food supply was chosen as the objective function (119). Since models 2-4 minimized TRD, constraints on CO_2eq were applied in order to also achieve reduced climate impacts from the school food supply. All models were to various degrees constrained to limit the deviation of individual foods and/or food group. The extent to which the foods and/or food groups in the optimized solutions were prevented from deviating from the observed food supply increased as the Model number increased (**Figure 3.3**). DRVs for school meals (***Table 4.4***) were applied as obligatory constraints in all models to achieve a nutritionally adequate school food supply. The amounts of foods supplied the decision variables in all four pathways.

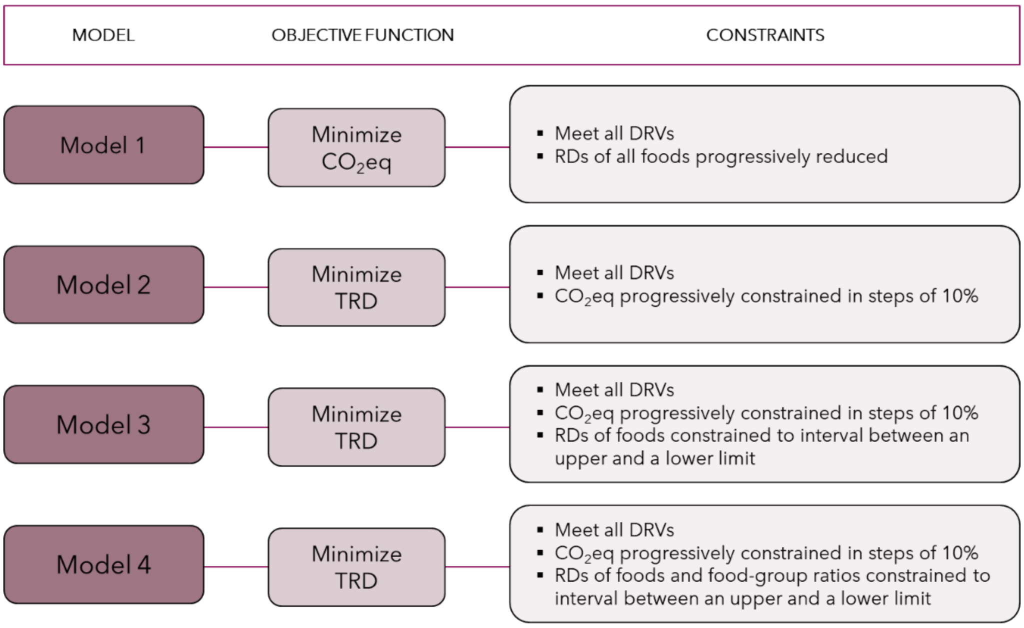

Figure 3.3. *Pathways for the optimization of the school food supply developed for Study II. DRV, dietary reference values; RD, relative deviation; TRD, total relative deviation;* CO_2*eq, carbon dioxide equivalents.*

Outputs in all models were the average daily CO_2eq and the cost of the food supply for one pupil, the average relative deviation (ARD), as well as the relative changes of the food groups: Cereals, Bread, Solid dairy (e.g., cheese), Other dairy (e.g., milk), Red meat (including offal), Poultry, Pulses, Roots and tubers, Vegetables (e.g., tomatoes, cucumber, lettuce), Fruits and berries, Fish, Oils, Solid fats (e.g., butter, margarine), Eggs, Other (e.g., seeds, salt, sugar, jams), Red meat, Poultry meat and Processed meat. These food groups were based on the categorization of foods used in the Climate Database. The average relative ratio deviation (ARRD) of the entire model was assessed for Models 2-4.

3.3 OPTIMAT: A PRE-POST INTERVENTION STUDY (STUDY III AND IV)

Study III and IV are based on a school-based intervention study performed during the spring term of 2019 in three primary schools (grades 0-9) from one of Stockholm county's 26 municipalities. Study III was performed to assess the effect of implementing a GHGE-reduced, nutritious, affordable and DA-optimized—i.e. sustainable—4-week school lunch menu on food waste, consumption and pupils' school meal satisfaction at school level. It was a pre-post, single-arm study (192), meaning that the selected outcomes were measured within the same schools both before the new menu was implemented (baseline) and then again during the time when the menu was being served (intervention). When the intervention period was over, focus group discussions (FGDs) were employed to explore pupils' and kitchen staff's experiences with the new menu and to identify potential barriers and facilitators to successful implementation of sustainable school meals (Study IV).

3.3.1 Recruitment and setting

Recruitment of schools was performed during the fall of 2018. Initially, meal managers (in charge of planning all public meals within their municipality) and school head chefs from three Stockholm-municipalities were invited to participate in information meetings where the aim and scope of the intervention were described. Three primary schools from one of the three municipalities participated in the intervention. These schools met inclusion criteria as they had on-site kitchens where kitchen staff usually prepared the school lunches on a daily basis. They were also able to provide recipes for a previously served standard four-week menu digitally; a criterion that was important for the optimization procedure.

3.3.2 Theoretical basis: Social Cognitive Theory (SCT)

The OPTIMAT-intervention was founded on the behavior change principles of Social Cognitive Theory (193). This theoretical framework posits that human behavior is determined by reciprocal interaction between Personal, Behavioral and Environmental factors (***Figure 3.4***). In this intervention, the aim was to investigate the effect of targeting the physical environment only by introducing a new 4-week sustainable school lunch menu. Therefore, information about the intervention to pupils and parents was contained to a minimum, and no additional intervention components (e.g. educational activities related to sustainable eating) were included in this first intervention study.

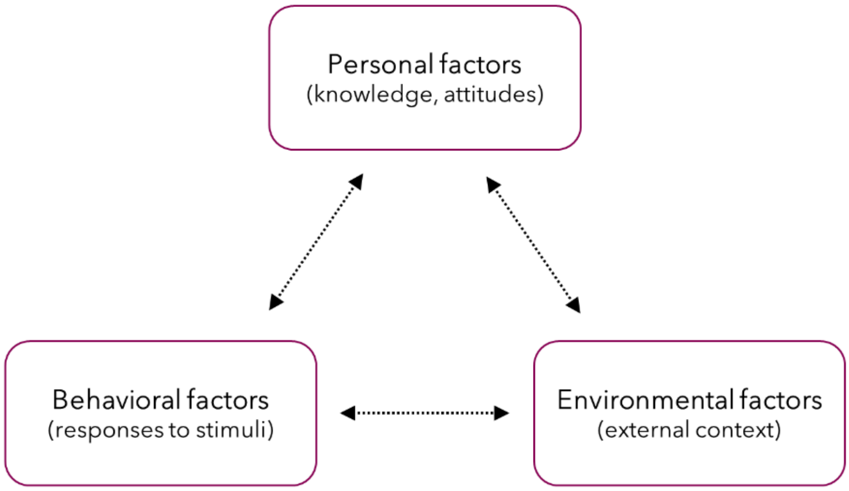

Figure 3.4. *Illustration of the interaction between Personal, Behavioral and Environmental factors that influence behavioral change—with information from Bandura (193).*

3.3.3 Developing a 4-week sustainable school lunch menu

The process of developing the new school lunch menu comprised three main steps. The first two steps predominantly built on the methodological developments in Study II. However, in Study III, the possibility of combining LP with public meal planning was further explored.

3.3.3.1 Step 1: The baseline school lunch menu

A previously served 4-week menu constituted the baseline menu. This menu had been prepared and served during the spring of 2018 at all the three included schools. The baseline contained 40 dishes for which recipes were obtained. The recipes included information on amounts of each food item in kilograms (kg) of raw food that were needed to prepare each dish. The recipes also contained details on the price per kilogram, as well as the total cost (kilogram*price per kilogram) of each food/drink. The weight of foods/drinks that had been used at multiple occasions for the 4-week menu were aggregated as per Study II (section 3.2.1), resulting in a food list comprising 142 food items. Similar to Study II, these individual food items were also aggregated into food groups for descriptive purposes (**Table 4.5**). Food types (i.e. sub-food categories) within food groups were also summarized by weight to describe absolute and relative changes occurring within food groups in more detail (**Table 4.5**). The average amount, cost, energy content/constraint, nutrient content/constraints and climate impact of these foods were derived as per Study II (section 3.2.1).

3.3.3.2 Step 2: Optimizing the baseline menu with Model 3

In Study III, Model 3 (**Figure 3.3**) was applied to the list of 142 foods used in the baseline menu. This model was considered most appropriate in terms of reducing the climate impact of the food supply while also keeping it as similar as possible to baseline. Hence, constraints were applied to achieve energy and nutritional adequacy, and a 40% reduced climate impact relative to baseline values. The 40% reduction was in line with the World Wildlife Fund's recommendation that the daily climate impact from a Swedish school lunch should amount to a maximum of 500 g of CO_2eq per meal to maintain weekly diet related GHGE-budgets at levels necessary for keeping the global average temperature increase below 1.5 degrees compared to preindustrial levels (194). The weight of individual food items was also constrained to decrease by a maximum of 75% or increase by a maximum of 100% from baseline as per Model 3. This was done to ensure that no food item from the baseline food list more than doubled in weight or was excluded entirely. The optimized food list thus contained the same foods as those present in the baseline list, although amounts of each food were in some cases changed by the LP-algorithm to meet nutrient-, GHGE- and DA-targets.

3.3.3.3 Step 3: Planning and preparation of meals for the new menu

The optimized food list was handed over to an experienced public meal planner that composed recipes for a new 4-week menu using all foods and their respective amounts as indicated on the (optimized) list. However, the meal planner was allowed to make minor changes to the optimized food amounts in agreement with the research team. The meal planner also had access to the baseline menu (plus recipes) since the aim was to create a new menu that aligned with the baseline menu as closely as possible.

The meal manager and school chefs of the participating schools were given the opportunity to discuss and approve the new menu before the intervention started. In agreement with the research team, each school chef was also provided with some flexibility to make minor alterations to the recipes in new menu. School chefs and kitchen assistants prepared the baseline and intervention menus in the school kitchen and served the dishes in the school canteen of each school.

3.3.4 Evaluating the acceptability of the new menu (Study III and IV)

Both quantitative and qualitative data were collected in order to investigate the acceptability of the new menu among pupils and/or kitchen staff (**Figure 3.5**). Firstly, data on food waste and consumption were gathered as this was considered to provide an objective measure of school meal acceptance (part of Study III). Secondly, pupils were asked to answer an online questionnaire to obtain a quantifiable measure of school meal satisfaction (i.e. a more subjective quantitative measure of acceptance) amongst pupils (part of Study III). Lastly, FGDs were carried out to attain an in-depth understanding of the experiences and perceptions of pupils and kitchen staff in the schools where the intervention had taken place (part of Study IV).

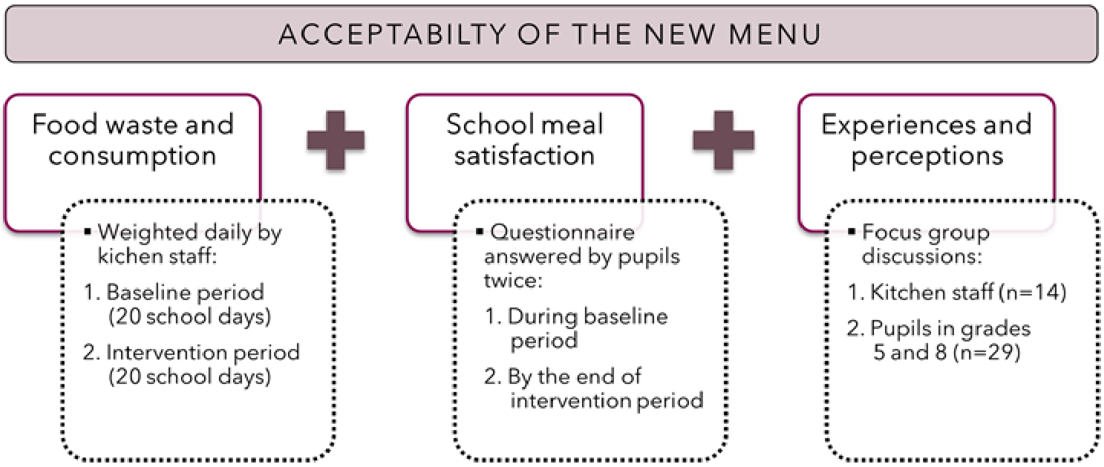

Figure 3.5. *Methods used to evaluate the acceptability of the new menu.*

3.3.4.1 Collecting data on food waste, consumption and pupils' school meal satisfaction

Daily measurements on food waste and consumption (**Table 3.3**) were carried out in each school by the kitchen staff during both the 4-week baseline period as well as during the 4-week intervention period. The kitchen staff carried out the measurements using kitchen scales based on an established method for determining food waste and consumption in Swedish school canteens (195).

Table 3.3. Outcomes measures on daily food waste and consumption assessed in the intervention.

	Measure (unit)	Description
Weighted	1. Kitchen waste (kg)	Food waste generated during preparation and cooking
	2. Prepared food (kg)	Food prepared in the kitchen
	3. Serving waste (kg)	Food that was prepared but not eaten by the pupils and had to be thrown away
	4. Leftover food (kg)	Food that had not yet been brought out to the canteen and could be re-used
	5. Total plate waste (kg)	Food discarded by the pupils in a bin when leaving the school canteen
	6. Plates used (nr)	Number of plates used by pupils in the school canteen
Calculated	7. Plate waste/pupil (g)	Total plate waste [5] / Plates used [6]
	8. Total consumption (kg)	Prepared food [2] - (Serving waste [3] + Leftover food [4] +Total plate waste [4])
	9. Consumption/pupil (g)	Total consumption [8] / Pates used [6]

School meal satisfaction among pupils in grade 5 (ages 10-11) and 8 (ages 14-15) was assessed using an online questionnaire. These grades were selected to enable a comparison with findings from Study I. A version of the questionnaire is used frequently (196) and has been shown to have good face validity. Pupils answered the questionnaire anonymously in the middle of the baseline period and again in the last week of the intervention period. The questionnaire covered questions concerning the school lunch, of which five explicitly referred to pupils' school lunch satisfaction (**Figure 4.9**).

3.3.4.2 Statistical analyses of food waste, consumption and pupils' school meal satisfaction

Descriptive statistics of food waste, consumption and pupils' school meal satisfaction were computed at aggregated (school) level and presented as means with 95 %. The significance level for all inferential analyses was set at <0.05. The analytic methods of pre-post studies are largely determined by the nature of the intervention as well as the type of outcome being assessed (192). The eight outcome measures on food waste and consumption (***Table 3.3***) for the two time periods (baseline and intervention) were compared within each school by means of interrupted time-series (ITS) analysis (197). The ITS-approach was employed as it has been established as a strong and useful method for the assessment of interventions that are being introduced at a distinct point in time and/or in contexts where it might not be feasible or meaningful to achieve a randomized study-sample (197). For all outcome measures relating to food waste and consumption, a "level and slope change analysis" was performed (197). Pearson's chi-squared test was used for the before-after assessment (also within each school) of the five questionnaire items concerning school meal satisfaction.

3.3.4.3 Focus group discussions: exploring pupils' and kitchen staff's experiences and perceptions

When the intervention period was over, FGDs were carried out with explore pupils and kitchen staff. The usefulness of FGDs is particularly pronounced when the aim is to obtain an understanding with regards to experiences and usefulness of a phenomenon that is shared by a defined group (198,199). Data attained through FGDs encompass perceptions as stated by the group and formed through the interaction between the group members (198,199). Focus group discussion were therefore considered the appropriate method for investigating experiences with the new menu and to identify potential barriers and facilitators to successful implementation of sustainable school meals, as perceived by kitchen staff and pupils.

The FGDs were carried out with kitchen staff as well as with pupils in grades 5 and 8, i.e. pupils from the same grades that had answered the online questionnaire in Study III. Both the providers (kitchen staff) and the receivers (pupils) of the intervention were targeted in order to gain a broad and exhaustive understanding of how the intervention was experienced and how successful implementation at scale could be achieved (200). A total of nine FGDs were conducted. Three of them were performed with the kitchen staff. Three FGDs were carried out with grade 5 pupils in the three schools (n=15, 60% girls), while the remaining three were held with grade 8 pupils in the three schools (n=14, 53% girls).

The FGDs were transcribed and analyzed inductively using (manifest) qualitative content analysis (QCA) (201,202). In inductive analysis, findings emerge from the data, thus allowing for a description of the underlying structures of experiences and processes that exist within a study-sample (199). Content that was found to be related to the research questions (i.e. meaning units) was abstracted into a condensed meaning unit, which was consequently assigned a code that captured the core of the condensed meaning unit. Lastly, the codes were compared and organized into categories and sub-categories. The QCA is exemplified in **Figure 3.6**.

Meaning unit	Condensed meaning unit	Code
There is lots of vegan or vegetarian food that's tasty, but since the vegan or vegetarian food doesn't taste very good in school, then no one eats it.	The vegetarian food must be tasty to be eaten	Taste important

Figure 3.6. *Example of how the qualitative data from the focus group discussions were analyzed with qualitative content analyses.*

3.3.5 Ethical considerations for the OPTIMAT-intervention

The OPTIMAT-intervention was approved by the Swedish Ethical Review Board in Stockholm County, No. 2019-01281. The ethical considerations for Study III and IV were founded on the Helsinki declaration which places great emphasis on the respect for all human subjects and the protection of their health and rights (203). It also states that vulnerable groups, such as children, should be resolutely protected in any research study (203). Hence, the ethical considerations have primarily revolved around the basic ethical principles of "Beneficence" and "Nonmaleficence" (204) with regards to the OPTIMAT-intervention and its potential impacts on the children subjected to it. Reflections have also revolved around the extent to which the research can be considered ethically justified with respect to a broader societal perspective.

3.3.5.1 The Principle of Beneficence

The limited scope of the intervention could limit the generalizability of the results obtained. The question is thus whether the intervention was sufficiently comprehensive to be able to generate wider societal benefits, whether it was ethically justified to use research funds (i.e. taxpayers' contributions) for this purpose and whether these resources could have been better spent elsewhere.

3.3.5.2 The Principle of Nonmaleficence

If pupils in the intervention schools would not have accepted the new optimized menu, this could have resulted in a reduced school lunch consumption, reduced nutrient intakes, and an increased food waste. This could thus risk implicating both health and environmental priorities. Participation in focus group discussions could have potentially also caused some discomfort to the pupils. There was a further risk that the limited scope of the study would generate unclear conclusions that could be misinterpreted within, as well as outside, the research community. These misinterpretations could in turn result in consequences such as changes to how public meals are planned.

3.3.5.3 Maximizing beneficence and minimizing risks

One strong argument for conducting the intervention despite these risks was that this type of research is likely to be essential in order to generate knowledge on how to reduce the climate impact from the school meal system—which is part of the greater food system—in Sweden. The conducted research could be seen as a first and necessary step if aiming to achieve advancements in both theory and practice seeing that nothing similar had been done previously. The research-findings are in turn thought to lead to an increased interest in the issue and/or to new funding opportunities which could result in possibilities to carry out more large-scale studies with additional benefits for human as well as environmental health. Sustainable school meals are something that likely will bring about benefits to the research subjects as well as to the greater society—in both the short and long term. It may also be important for children today to be able to take action themselves as a means to ease climate anxiety which is a growing concern.

The intervention was carefully planned in order to maximize beneficence and minimize risks for potential maleficence. Actions that were taken include aspects such as conscientious planning of the intervention together with relevant stakeholders (school chefs, meal planners). Another implemented action was to involve a professional meal planner for designing the new menu as for maximizing the compatibility between the new dishes and existing prerequisites of school kitchens, kitchen staff, and children's taste-preferences. Follow-up and surveillance of waste and consumption were implemented continuously during the intervention, alongside a set of predetermined counter measures for the potential encountering of adverse outcomes (e.g. allowing the school chefs to deviate where necessary from the optimized menu to increase school lunch acceptance). Study subjects for group discussions were informed about the purpose of the study, as well as of their right to withdraw at any time. They were ensured confidentiality and anonymity and information with regards to the recording of the sessions were provided to all informants. Written informed consent was requested from the kitchen staff and since the FGDs involved children below the age of 15, written consent was also requested from pupils' legal guardians prior to the FGDs. Lastly, clarity and transparency in the communication of research results and conclusions have been a constant priority.

3.3.5.4 Concluding reflections

The OPTIMAT-intervention was carried out giving due consideration to ethical risks. From a utilitarian perspective (204), the OPTIMAT-intervention is judged ethically justifiable. It is believed that this type of research provides valuable opportunities to create wider benefits to the society with respect to both health and environmental priorities without causing harm to individuals. Extensive diet sustainability research, employing more theoretical approaches, exists, but this research offers the first school-based intervention study ever to explore the introduction of sustainable school meals in a real-world context. Regardless of the generalizability of our conclusions, it can be argued that the innovative nature of OPTIMAT has substantial potential to do good in the sense that it will raise the question of sustainable public meals and their practical applicability to a new level—nationally as well as globally—with minimal risk to individuals.

4 RESULTS

4.1 THE ROLE OF THE SCHOOL LUNCH IN CHILDREN'S OVERALL DIETARY INTAKE (STUDY I)

4.1.1 School lunch intake compared to Swedish school meal standards

The extent to which pupils' absolute dietary intakes from the school lunch in different sex and age groups reach Swedish school meal standards used for planning school meals (174) in relative terms can be seen in **Figure 4.1**. In general, pupils' intakes of energy and nutrients did not align with the DRVs in the Swedish school meal standards. Folate was the only nutrient where pupils' mean absolute intakes reached the reference amount. This was true for all groups except for Girls in grade 8.

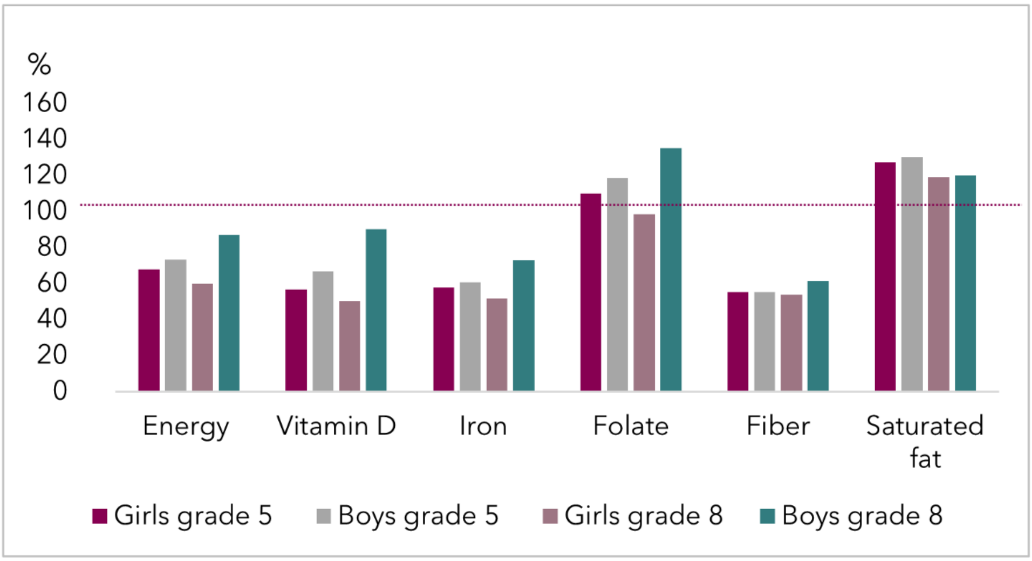

Figure 4.1. *Pupils' mean absolute dietary intakes from the school lunch in different sex and age groups relative (%) to the Swedish school meal standards used for planning school meals (174). The line represents a 100% alignment with dietary reference values.*

4.1.2 Nutrient and energy density at lunch vs. the rest of the school day

The mixed-effects linear regression analyses showed that the energy-adjusted intake of selected nutrients and food groups was significantly higher ($p<0.001$) and the energy density significantly lower ($p<0.001$) for pupils' intake at lunch compared to their dietary intake during the rest of the school day (**Table 4.1**).

Table 4.1. Energy-adjusted intake of nutrients and food groups and the energy density, respectively, at lunch and during the rest of the school day for the entire sample of pupils (N=2,002).

Nutrient/ food	Unit	Intake Lunch		Intake Rest of the day		Parameter estimates	
		Mean	95% CI	Mean	95% CI	*ß1*	*P*
Vitamin D	µg/10MJ	9.8	9.4-10.2	7.2	7.0-7.4	-2.54	<0.001
Iron	mg/10MJ	10.7	10.5-10.9	9.8	9.6-10.0	-0.83	<0.001
Folate	µg/10MJ	376	367-385	321	316-326	-54.32	<0.001
Fiber	g/10MJ	25.6	25.0-26.2	22.1	21.7-22.5	-3.47	<0.001
Saturated fat	g/10MJ	34.1	33.5-34.7	36.4	36.0-36.8	2.30	<0.001
Vegetables	g/10MJ	399	374-424	142	136-148	-256.85	<0.001
Fish	g/10MJ	85	79-91	17	15-19	-68.02	<0.001
Meat	g/10MJ	153	146-160	92	89-95	-60.95	<0.001
Energy density	(kJ/g)	6.7	6.6-6.8	8.8	8.6-8.9	2.05	<0.001

Mixed-effects linear regression analyses with pupils' energy-adjusted intakes of nutrients and food groups or the energy density of their dietary intake as dependent variable, period (lunch intake vs. rest of the day) as independent fixed effect; school and pupils' personal case number (ID) as independent random effects. ß1= beta coefficient from linear regression model.

4.1.3 Daily intake, school lunch intake and share of daily intake provided by lunch

Figures **4.2-4.4** depict the results from the mixed-effects linear regression analyses performed to investigate differences in pupils' dietary intake of energy and energy-adjusted intakes of nutrients and food groups by sex and level of parental education. The models investigated differences in total daily intake, intake at lunch, as well as differences in the share of daily intake provided by lunch.

4.1.3.1 Total daily intake

Total daily dietary intake (**Figure 4.2**) differed by sex, with boys having significantly higher mean intakes of energy, vitamin D, and red/processed meat as compared to girls. However, boys had a significantly lower mean daily intake of folate, dietary fiber and vegetables than girls.

Total daily intakes also differed by level of parental education, with pupils of parents with lower-level education (≤12 years of education) having significantly lower mean daily intakes of energy, iron, folate, dietary fiber and vegetables but significantly higher mean intakes of fish and red/processed meat as compared to pupils of parents with >12 years of education.

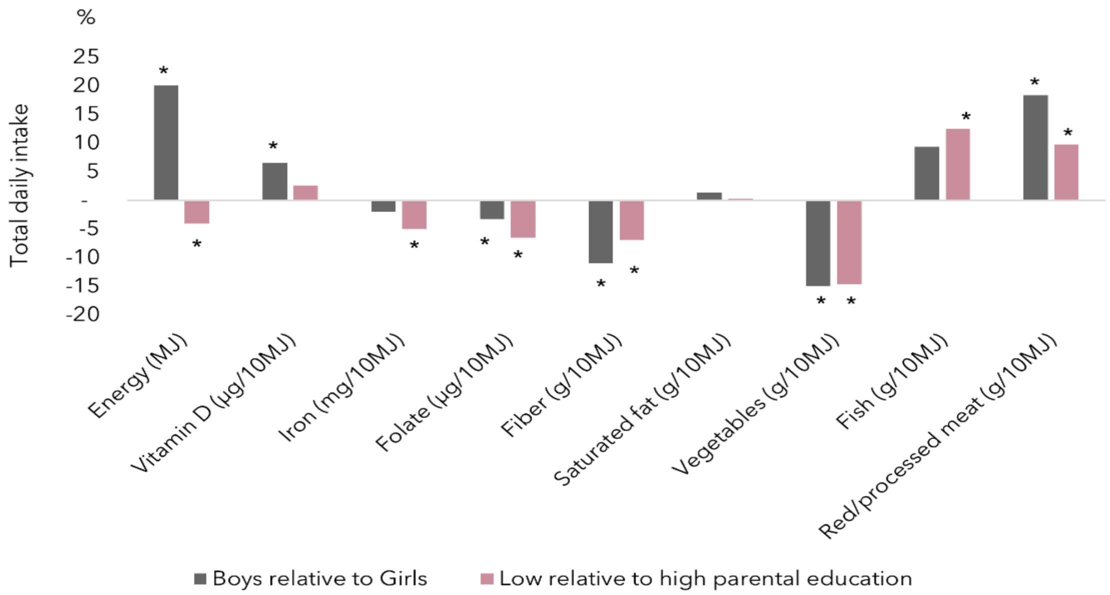

Figure 4.2. *Relative (%) difference in the total daily mean energy-adjusted intake of nutrients and foods by sex (boys relative to girls) and level of parental education (low relative to high parental education), respectively. *P<0.05, from mixed-effects linear regression analyses with daily energy intake, or energy-adjusted nutrient or food intake as dependent variable; sex, grade and parental education as independent fixed effects; school as independent random effect.*

4.1.3.2 Intake at lunch

Intakes from the school lunch (**Figure 4.3**) differed by sex, with boys having significantly higher mean intakes of energy, vitamin D, fish and red/processed meat, but significantly lower mean intakes of dietary fiber and vegetables.

Although mean intakes of energy, iron, folate, dietary fiber and vegetables were lower for pupils of parents with lower-level education over the entire day, at lunch, only the mean intakes of iron and dietary fiber were significantly lower in this group. Furthermore, pupils of parents with lower-level education had higher mean intakes of vitamin D and fish during lunch as than pupils of parents with >12 years of education.

Figure 4.3. *Relative (%) difference in the daily intake at lunch of energy, energy-adjusted intakes of nutrients and energy-adjusted intakes of food groups by sex (boys relative to girls) and level of parental education (low relative to high parental education), respectively. *P<0.05, from mixed-effects linear regression analyses with energy intake, or energy-adjusted nutrient or food intake at lunch as dependent effect; sex, grade, parental education and energy-adjusted intake during the rest of the day as independent fixed effects; school as independent random effect.*

4.1.3.3 Share (%) of daily intake provided by lunch

Several statistically significant differences were observed when expressing intakes from lunch as a percentage of total daily intake (**Figure 4.4**). Compared to girls, boys had significantly greater shares of their mean daily intakes provided by lunch in terms of energy, vitamin D, folate, and fish.

Statistically significant differences were also found by level of parental education. As compared with pupils of parents with higher levels of education, pupils of parents with lower-level education had significantly greater shares of their mean daily dietary intakes provided by lunch in terms of vitamin D, saturated fat, vegetables and fish.

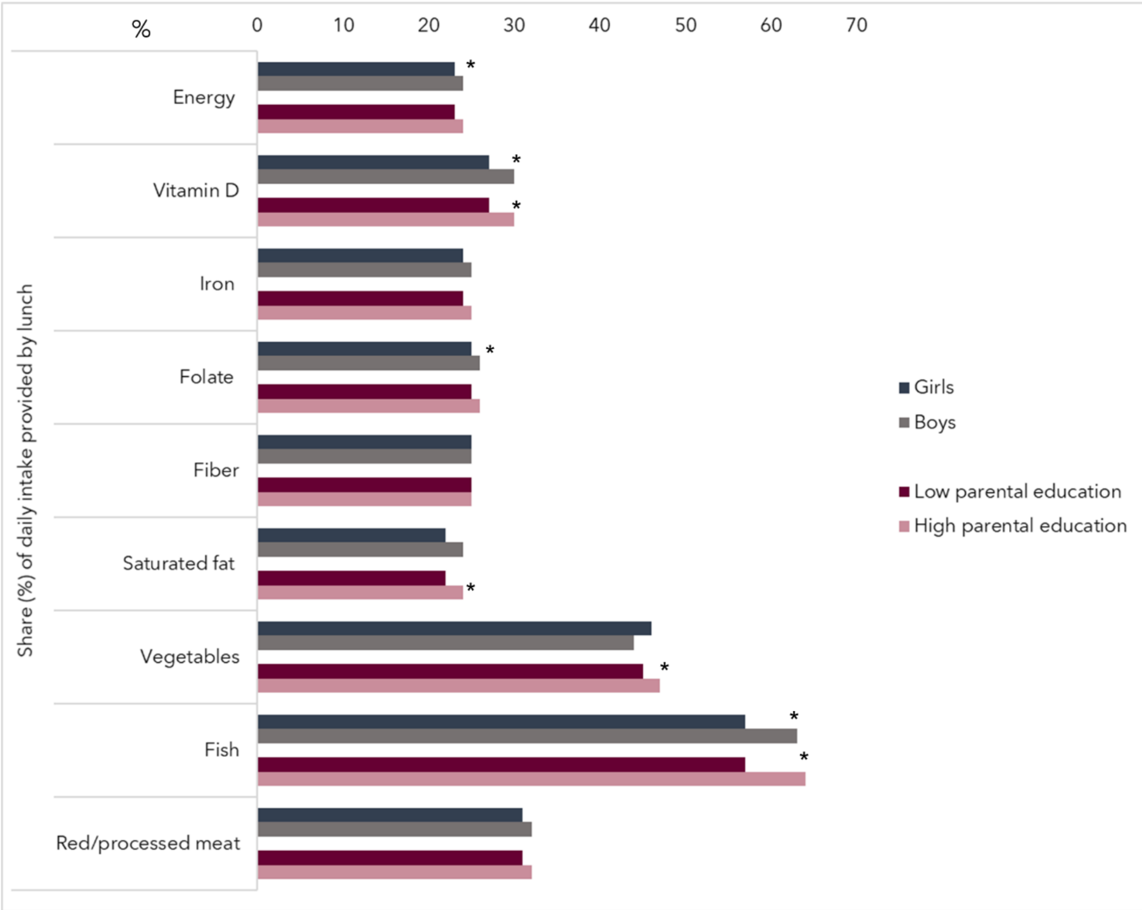

Figure 4.4. *The share (%) of pupils' daily intake provided by lunch in terms of energy, nutrients and food groups by sex and level of parental education. Mixed-effects linear regression model with share (%) of daily intake provided by lunch as dependent effect; sex, grade and parental education as independent fixed effects; school as independent random effect. *P<0.05.*

4.2 OPTIMIZING SWEDISH SCHOOL FOOD SUPPLIES (STUDY II)

4.2.1 Observed and optimized food supplies

Table 4.2 provides an overview of the outputs from the four pathways modeled for the school food supplies. The climate impact of the observed school food supply was reduced by 89 to 95% (depending on the school) in Model 1 when aiming to meet DRV-targets only (**Table 4.2**). This model lacked diversity and included foods only from 5-6 out of the 15 pre-defined food groups (**Figure 4.5**). Its ARD ranged between 29 to 887% and individual foods deviated by ~80.000 to 200.000% from observed amounts (**Table 4.2**).

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Table 4.2. Outputs from the four modeled pathways developed for the optimization of the school food supplies in Study II.

	Highest GHGE reduction (%)			Lowest ARD (%)			Highest ARD (%)			Highest % change of individual foods (output)			Lowest ARRD (%)			Highest ARRD (%)			Highest % change for food group ratios (output)		
School #	1[a]	2[b]	3[c]	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Model 1	89	93	95	40	45	70	887	293	480	209,156	87,254	80,149	na	na	na	na	na	Na	na	na	na
Model 2	80	90	90	1.5	2.5	2.9	78	64	70	810	1021	496	40	32	42	950	410	278	332	597	318
Model 3	50	60	50	2	3.7	3.8	26	76	145	200	200	200	22	42	62	113	145	125	219	263	164
Model 4	40	50	nfs	3.5	6.8	13	75	74	nfs	200	200	nfs	0	0	nfs	36	34	Nfs	50	50	nfs

[a]Baseline CO_2eq of food supply = 810 g; [b]Baseline CO_2eq of food supply = 1,022 g; [c]Baseline CO_2eq of food supply = 967 g. na; not assessed; nfs; no feasible solution found for a GHGE reduction of more than 10%, the model outputs for a 10% reduction in carbon dioxide equivalents in School 3 would not be comparable to the outputs from Schools 1 and 2 and are thus not reported in this table. GHGE, greenhouse gas emissions; ARD, average relative deviation; ARRD, average relative ratio deviation.

In Model 2—where TRD was minimized instead of GHGE—it was also possible to achieve GHGE reductions of around 80 to 90%, comparable to those achieved in Model 1 (**Table 4.2**). But here, the lowest achievable ARDs for the entire model were lower than in Model 1, ranging between 1.5% to 2.9% as compared to 40 to 70% in Model 1. However, there were individual foods that still deviated notably from baseline.

These high deviations were avoided in Model 3 (**Table 4.2**). Here, each individual food item had to be provided by at least 25% of its observed amount and no foods could increase by more than 100 or 200 percent. Hence, adding these constraints on the RD of individual food items resulted in that Model 3 contained all foods from the baseline supply (since foods could not decrease by more than 75%). However, this constraint resulted in that almost all of them either increased or decreased in amount as compared to observed values. As a consequence, ARDs in Model 3 were slightly higher than in Model 2 at comparable CO_2eq-reductions (Table 2, Appendix II). The ARDs of Model 3 were still below 10% under a 40% CO_2eq-reduction. Model 3 implied deviations to individual food group ratios of 164 to 219%.

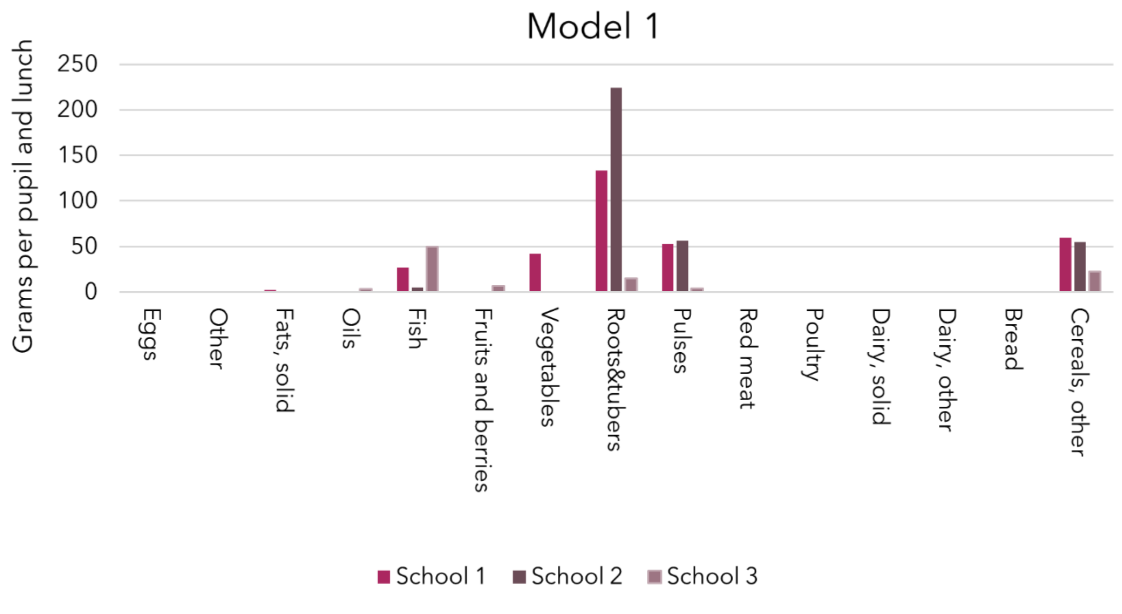


Figure 4.5. *Food group pattern (grams per pupil and lunch) when minimizing greenhouse gas emissions while applying nutritional constraints only in Model 1.*

Constraints on the extent to which food group ratios could differ (as compared to baseline) were therefore applied in Model 4. Adding these constraints, however, limited the LP-algorithm's capacity to lower the CO_2eq of the school food supply (**Table 4.2**). The ARDs were higher in Model 4 as compared to Model 3.

Table 4.3 depicts how the four models performed in relation to each other with regards to GHGE-reduction, ARD, ARRD as well as the RD of individual foods or food group ratios. Model 3 was considered to provide the best balance between GHGE-reductions of the food supplies and the deviation from observed supplies.

Table 4.3. Overview of the performance of the four modeled pathways developed for the optimization of the school food supplies in Study II.

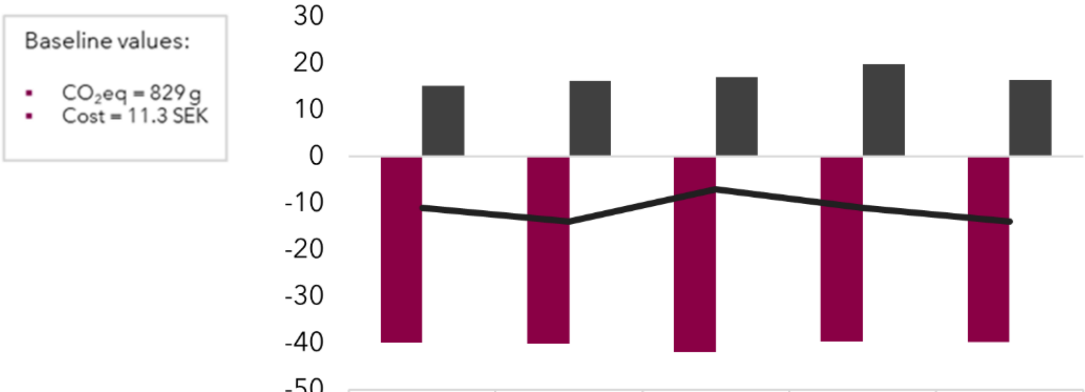
	GHGE reduction ≥50% possible for all schools	ARD ≤10%*	ARRD ≤10%*	High deviations of individual foods	High deviations of food group ratios
Model 1	Yes	No	No	Yes	Yes
Model 2	Yes	Yes	No	Yes	Yes
Model 3	Yes	Yes	No	No	Yes
Model 4	No	No	Yes	No	No

*For a 40% CO_2eq-reduction. GHGE, greenhouse gas emissions; ARD, average relative deviation; ARRD, average relative ratio deviation.

4.3 OPTIMIZATION, MENU PLANNING AND DELIVERY OF A SUSTAINABLE SCHOOL LUNCH MENU (STUDY III)

4.3.1 Changes enforced by the LP- algorithm in Study III

The linear optimization performed for the intervention study (applying Model 3 from Study II) reduced the average CO_2eq of the school meals by 40% and reduced the cost by 11% (**Figure 4.6**). Since not all DRVs used for planning school meals were met in the baseline menu (amount of saturated fatty acids was 7% over, and the amount of iron 10% under, the DRV), the linear modeling ascertained that these, as well as all other, DRVs were fulfilled in the optimized food list (**Table 4.4**).



	Optimized	Planned	Delivered School 1	Delivered School 2	Delivered School 3
% Change (CO2eq)	-4.0	-4.0	-4.2	-4.0	-4.0
ARD	1.5	1.6	1.7	2.0	1.6
% Change (Cost)	-1.1	-1.4	-0.7	-1.1	-1.4

Figure 4.6. *Relative (%) changes in carbon dioxide equivalents (CO_2eq) and cost, as well as the average relative deviation (ARD) of the optimized food list, planned (new) menu and served (delivered) menu in the three schools. *Enforced to meet the World Wildlife Fund's target level of maximum 500 grams carbon dioxide equivalents per meal (CO_2eq/meal); SEK = Swedish krona.*

Table 4.4. Dietary Reference Values (DRVs) used for planning school meals in relation to baseline, optimized (applied as constraints) and delivered menu in Schools 1-3 participating in the intervention.

Constraints*			Baseline	Optimized	Planned	Delivered School 1	Delivered School 2	Delivered School 3
Nutrient	Limit		% of limit	% of limit	% of limit	% of limit	% of limit	% of limit
Energy (kcal)	Equal to	674	100	100	97*	98*	98*	97*
Carbohydrates (%E)	Lower	45	96	102	96	96	99	96
	Upper	60	75	79	76	77	79	77
Fat (%E)	Lower	22	148	139	137	140	137	137
	Upper	40	96	90	91	93	90	91
Protein (%E)	Lower	10	166	159	156	160	159	156
	Upper	20	87	83	83	86	85	83
Fiber (%E)	Lower	2	150	179	170	168	171	169
Saturated fatty acids (%E)	Upper	10	107*	85	86	88	86	86
Monounsaturated fatty acids (%E)	Lower	10	171	166	165	169	164	165
	Upper	20	89	87	88	91	87	88
Polyunsaturated fatty acids (%E)	Lower	5	147	147	146	147	145	146
	Upper	10	85	88	89	90	88	88
Vitamin A (µg)	Lower	188	231	150	147	146	149	147
Vitamin D (µg)	Lower	3.1	149	148	145	144	145	145
Vitamin E (mg)	Lower	2.2	266	267	262	263	265	262
Thiamine (mg)	Lower	0.3	153	156	150	150	152	150
Riboflavin (mg)	Lower	0.4	123	113	110	113	112	110
Vitamin C (mg)	Lower	16	303	259	211	208	228	211
Niacin (mg)	Lower	4.6	135	133	117	119	130	117
Vitamin B6 (mg)	Lower	0.4	178	175	155	156	165	155
Vitamin B12 (µg)	Lower	0.6	238	192	189	193	191	189
Folate (µg)	Lower	62.7	257	282	268	267	268	268
Phosphor (mg)	Lower	199	279	268	261	265	266	260
Iodine (µg)	Lower	43.2	254	251	240	237	243	241
Iron (mg)	Lower	3.4	90*	100	97*	99*	97*	96*
Calcium (mg)	Lower	282	138	113	112	113	112	113
Potassium (mg)	Lower	971	130	131	118	118	122	117
Magnesium (mg)	Lower	87.7	138	149	141	141	143	140
Salt (g)	Upper	3.6	74	69	72	76	72	73
Selenium (µg)	Lower	12.5	108	100	99*	101	102	99*
Zink (mg	Lower	3.4	106	100	98*	99*	98*	98*

* Energy and nutrient constraints based on dietary reference values in the Swedish school meal standards (174).

The changes enforced by the LP-algorithm resulted in a new food list in which each food item on average deviated by 15.2% from baseline (**Figure 4.6**). These changes are illustrated on at food group level in **Table 4.5**. The food groups Fat and oils and Vegetables and root vegetables increased in weight while the food groups Seafood, Fruits and berries, Meat, Seasoning and sauces, Dairy and Cereals were reduced in weight. The quantities of the remaining three food groups remained unchanged. Two food groups experienced intra-food group substitutions. For example, while the quantity of Vegetables and root vegetables increased overall, the amounts of some food items in that food group reduced in weight. However, other food items in the same food group increased so much that they compensated for the reduced amount and ultimately resulted in a total food group quantity that exceeded its baseline value. **Table 4.5** shows the intra-food group changes in further detail.

Table 4.5. Changes occurring within food groups (baseline vs. optimized food supply) in the optimization performed for the intervention (Study III).

Main food group	Food types within food groups	Baseline (kcal)	Optimized (kcal)	Baseline (g)	Optimized (g)	Absolute Diff (g)	% Diff
Beverages (excluding milk)		0.29	0.29	0.41	0.41	0.00	0
Fats and oils	Butter	25.01	25.01	3.75	3.75	0.00	0
	Vegetable fats	119.19	128.08	14.54	15.55	1.01	7
Seafood		10.93	7.79	11.25	9.73	-1.52	-13
Fruits and berries	Citrus and bananas	9.97	2.88	6.86	22.80	15.93	232
	Other fruits[a]	3.48	3.48	6.71	6.71	0.00	0
Vegetables and root vegetables	Pulses	52.14	86.25	45.80	69.11	23.30	51
	Potatoes	61.63	99.29	79.43	131.52	52.09	66
	Other vegetables[b]	53.72	35.21	137.68	80.49	-57.19	-42
Meat	Red meat	29.18	11.26	15.25	5.31	-9.94	-65
	Poultry	14.53	14.53	9.75	9.75	0.00	0
	Meat substitutes	12.07	12.59	7.75	8.25	0.50	7
Seasonings and sauces		11.44	10.77	8.59	6.34	-2.25	-26
Dairy	Dairy Solid[c]	19.66	8.11	7.20	3.49	-3.71	-52
	Dairy Other[d]	93.03	78.00	189.81	168.39	-21.43	-11
	Dairy substitutes[e]	5.30	5.30	2.65	2.65	0.00	0
Nuts and seeds		1.45	1.45	0.23	0.23	0.00	0
Sugars and sweets		0.40	0.40	0.10	0.10	0.00	0
Cereals	Rice	35.45	8.86	10.00	2.50	-7.50	-75
	Other cereals[f]	114.67	133.99	32.05	37.54	5.49	17

[a]Apples, pears and canned pineapple.
[b]Includes e.g. tomatoes, cucumbers, carrots, onions.
[c]Includes e.g. feta cheese, cottage cheese
[d]Includes e.g. cream and milk.
[e]Includes e.g. oat milk, and coconut milk which originally belonged to the food group “Nuts and seeds”.
[f]Includes e.g. pasta, crisp bread, wheat flour.

4.3.2 Adjustments made during planning and delivery of the meals

At the meal planning stage, a few adjustments to the optimized food list were made for practical reasons. The meal planner reduced the amount of potatoes by 29%, increased the amount of cultured milk by 65% and added rye bread and tortilla bread which were not part of the baseline list of 142 food items. Similarly, a few modifications to the recipes (in the new menu) were deemed necessary by the school chefs. Here, the changes entailed mainly the swopping of one food by a comparable one (e.g. using red onion instead of yellow onion). The changes made at the meal planning and meal preparation stages marginally affected the GHGE, cost, ARD and nutritional adequacy of the optimized school food supply (**Figure 4.6**, **Table 4.5**).

4.3.3 Food waste, consumption and pupils' school meal satisfaction: baseline vs. intervention period

On average, 15-19% of all prepared food was wasted (serving waste plus plate waste) during the baseline period (Table 2, Appendix III). The corresponding numbers were similar for the intervention period during which 17-21% of all prepared food was wasted. No significant differences in plate waste, serving waste or consumption were seen in any of the schools when comparing the baseline against the intervention period (Table 2, Appendix III). As for the remaining measurements, the average kitchen waste increased significantly in School 1 during the intervention. Furthermore, the slopes significantly changed between baseline and intervention period for the amount of prepared food in School 1 (**Figure 4.7**) and for the amount of leftover food in School 3 (**Figure 4.8**).

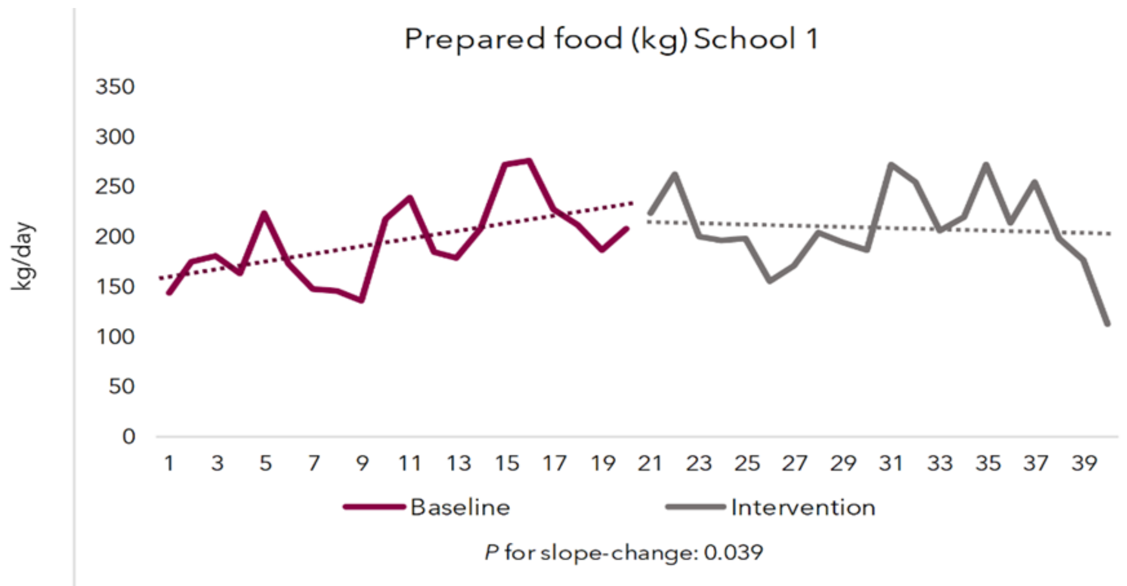


Figure 4.7. *Daily amount of prepared food (in kg) during the baseline (measurement day 1-20) and intervention (measurement day 21-40) periods in School 1.*

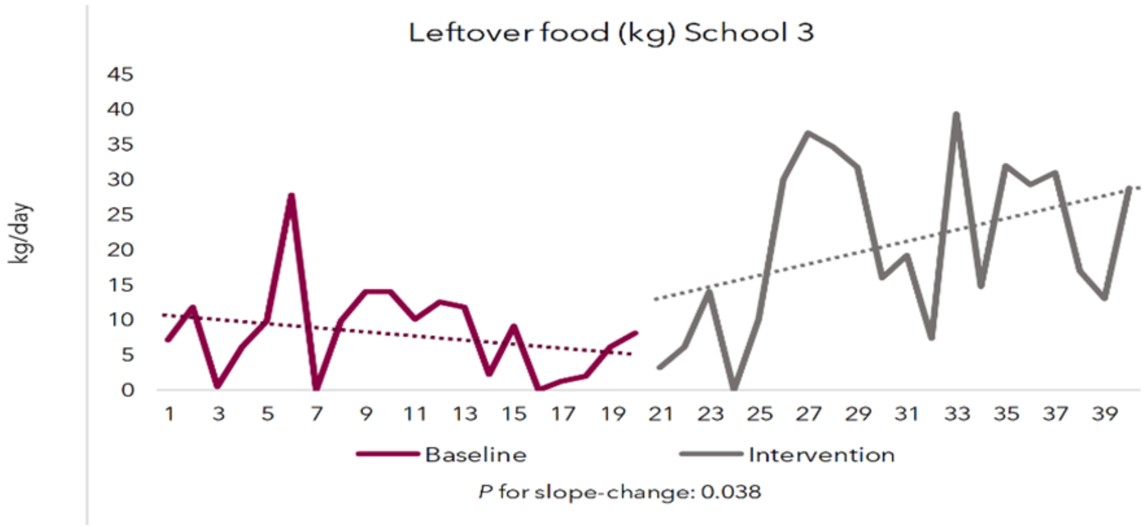


Figure 4.8. *Daily amount of leftover food (in kg) during the baseline (measurement day 1-20) and intervention (measurement day 21-40) periods in School 3.*

No statistically significant differences in school meal satisfaction were found between the baseline and the intervention period when assessing the different dimensions of school meal satisfaction. The overall rating of the school lunch was similar across schools and periods, with 35 and 37% of the pupils rating it as “Very good/Good” during baseline and 30 and 42% of pupils rating it as “Very good/Good” during the intervention period (**Figure 4.9**, Panel A). The proportion of pupils rating it as “Less good” varied between 33 and 38% at baseline and 31 and 38% during the intervention period while the numbers for “Bad” ranged between 26 and 32% at baseline and 27 and 32% during the intervention period.

Pupils’ opinions of the taste of the school lunch was also similar across schools and periods (**Figure 4.9**, Panel B), with 26 and 33% of the pupils stating that it “Always/almost always” tasted good at baseline and 24 and 34% of the pupils stating that it “Always/almost always” tasted good during the intervention period. The proportion of pupils stating that it “Rarely/never” tasted good was 67 and 74% at baseline and 66 and 76% during the intervention period.

The proportion of pupils that reported eating from the school lunch ≤3 days a week ranged between 40 and 50% at baseline and 41 and 48% during the intervention period (**Figure 4.9**, Panel C). Pupils reporting eating from the school lunch 4-5 days a week ranged between 50 and 60% at baseline and 52 and 59% during the intervention period.

Pupils’ feeling of satiety after having eaten the school lunch was also similar across schools and periods (**Figure 4.9**, Panel D), with 39 and 51% of the pupils stating that they “Always/almost always” felt full at baseline. Similarly, 41 and 47% of pupils stated that they “Always/almost always” felt full during the intervention period. The proportion of pupils stating that they “Seldom/never” felt full was 49-61% at baseline and 53 and 59% during the intervention period.

The share of pupils stating that they “Always/almost always” tended to leave plate waste in connection with the school lunch ranged between 32 and 36% at baseline and 33 and 47% during the intervention period (**Figure 4.9**, Panel E). The proportion of pupils reporting to “Seldom/never” leave plate waste was 64 and 68% at baseline and 53 and 67% during the intervention period.

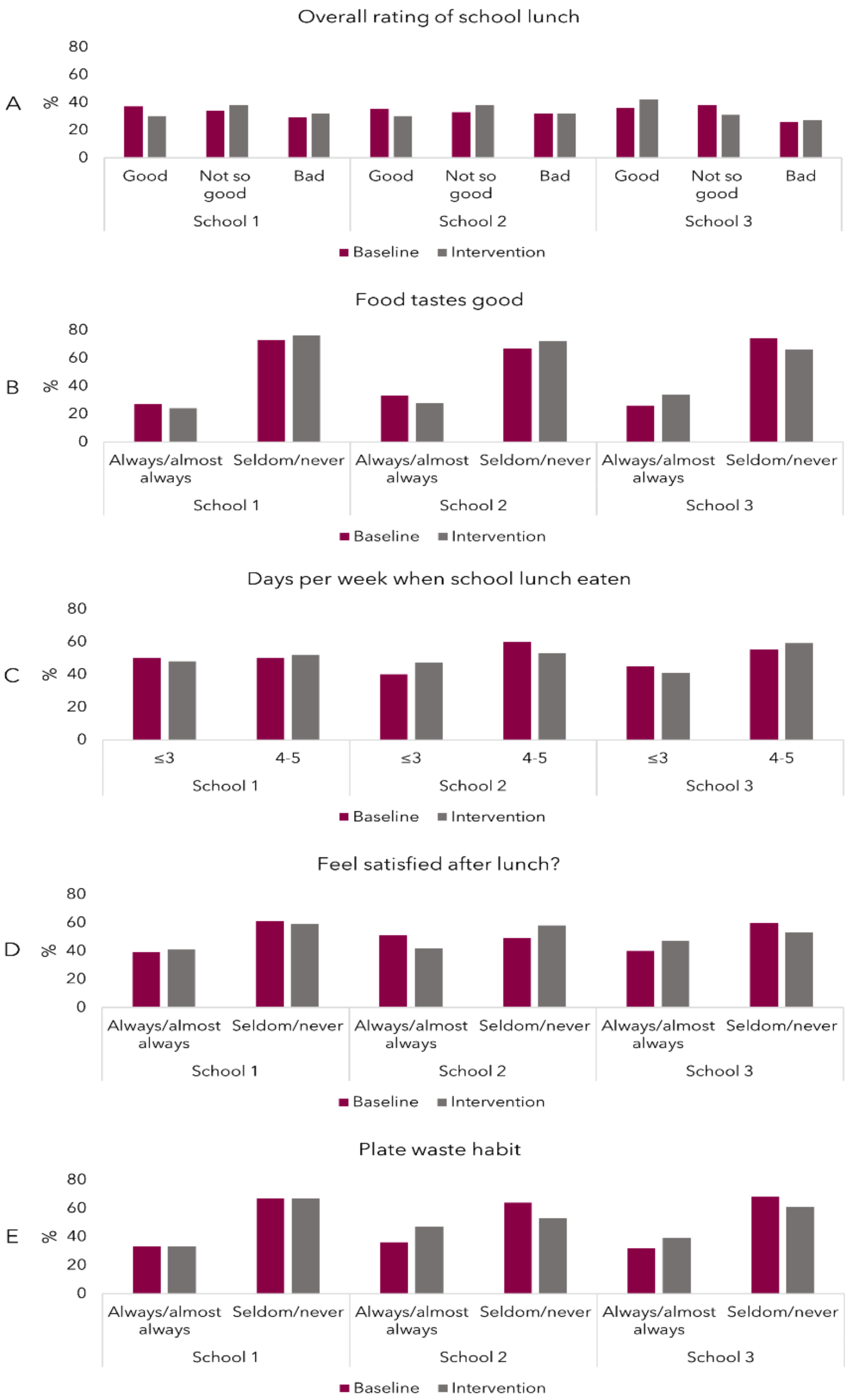


Figure 4.9. *School meal satisfaction during baseline and intervention periods amongst pupils in grades 5 and 8 in Schools 1-3. No statistically significant differences were found between periods.*

4.4 PUPILS' AND KITCHEN STAFF'S EXPERIENCES AND PERCEPTIONS: FINDINGS FROM THE FOCUS GROUP DISCUSSIONS (STUDY IV)

Five main categories and eleven subcategories emerged through the qualitative content analysis with pupils and kitchen staff from the intervention schools (**Figure 4.10**). In summary, the first main category described pupils' and kitchen staff's experiences of the new menu. Experiences with the intervention varied among pupils and kitchen staff. In general, pupils noticed small or no differences at all (regarding the school meals) during the period when the new menu was served. On the other hand, some pupils experienced an increased dissatisfaction with school meals among their peers during the intervention period. Kitchen staff experienced several challenges in working with the new recipes but also perceived it as an interesting learning experience They also perceived that pupils were less satisfied with the meals during the intervention period. The remaining categories described barriers and facilitators to successful implementation of sustainable school meals. Barriers included aspects related to pupils' habitual eating behaviors (e.g. their unfamiliarity with eating plant-based meals), sensory factors and the lack of knowledge, financial resources, adequate equipment and time for kitchen staff to prepare plant-based dishes. Gradually introducing children to new plant-based meals, considering the taste, naming and aesthetics of dishes carefully, and finding ways to motivate pupils to eat more plant-based foods were discussed as facilitators to successful implementation. An enhanced knowledge as well as an increased stakeholder involvement, ranging from pupils and kitchen staff to decision makers in the municipality, were also perceived to facilitate successful implementation of sustainable school meals.

Figure 4.10. Five main categories and eleven subcategories which emerged through the qualitative content analysis.

5 DISCUSSION

5.1 MAIN FINDINGS OF DOCTORAL THESIS

This thesis aimed to contribute to knowledge of how sustainable dietary habits could be achieved through the school meal system in theory and practice. Four distinct studies were carried out, each with its own aim and research findings. **Figure 5.1** summarizes the main findings of this doctoral thesis.

Study I showed that the school lunch constitutes an important part of pupils' overall dietary intake by providing a considerable share of their daily intakes of vegetables and fish. Furthermore, the nutrient density was significantly higher, and energy density significantly lower, for pupils' school lunch intakes compared to intakes from meals consumed during the rest of the day. This suggests that school meals make an important contribution to children's diets on weekdays. On the other hand, Study I showed that children's intakes from the school lunch did not meet all DRVs used for planning school meals. The school lunch is also a considerable source of red/processed meat, especially among boys. They consume more red/processed meat, but less fiber and vegetables as compared to girls, both at lunch as well as over the entire day. Lastly, differences in dietary intake based on pupils' parental education suggests that school meals can play a role in compensating for poorer dietary quality in the home environment.

The findings of Study II showed that substantial reductions (up to 40%) in the GHGE of Swedish school food supplies can be achieved, using LP, with only small changes to the observed supply while also ensuring its nutritional adequacy and affordability. The minimization of TRD in Models 2-4 achieved more similar food supplies compared to minimizing total GHGE in Model 1, at comparable levels of GHGE reduction. Model 2 omitted entire food categories and/or resulted in extreme changes in single foods. This highlights the value of limiting the deviation of individual food items as done in Model 3. Cost was lower or comparable to observed values across all models and schools. However, constraining the relative deviation of food-group ratios to achieve a higher degree of DA in Model 4 prevented the LP-model's capacity to reduce GHGE. The optimization of school food supplies thus seems to result in certain synergies but also show that trade-offs will likely also be needed to provide acceptable solutions.

Study III demonstrated that it was possible to combine the established optimization strategy from Study II (Model 3) with meal planning to achieve a climate friendly, nutritionally adequate and affordable school lunch menu. This new menu, which was prepared and served in three Swedish primary schools, was also judged acceptable to pupils since it did not significantly increase food waste decrease their consumption of, or satisfaction with, school lunches. However, about 20% of all prepared food during both baseline and intervention periods was wasted which thus raises concerns with regards to sustainability.

Experiences with the intervention varied among pupils and kitchen staff. The new menu was generally not noticed by pupils although kitchen staff experienced an increased dissatisfaction with the school lunches among pupils during the intervention period. Some hurdles to large scale implementation of sustainable school meals may thus exist. The qualitative findings from Study IV describe several barriers to successful implementation of sustainable school meals linked to e.g. pupils’ unfamiliarity with eating plant-based meals, sensory factors and the lack of financial resources, adequate equipment and time for kitchen staff to prepare such meals. Aspects such as increased exposure to plant-based foods, knowledge, motivation, and stake-holder involvement were seen as facilitators to successful implementation.

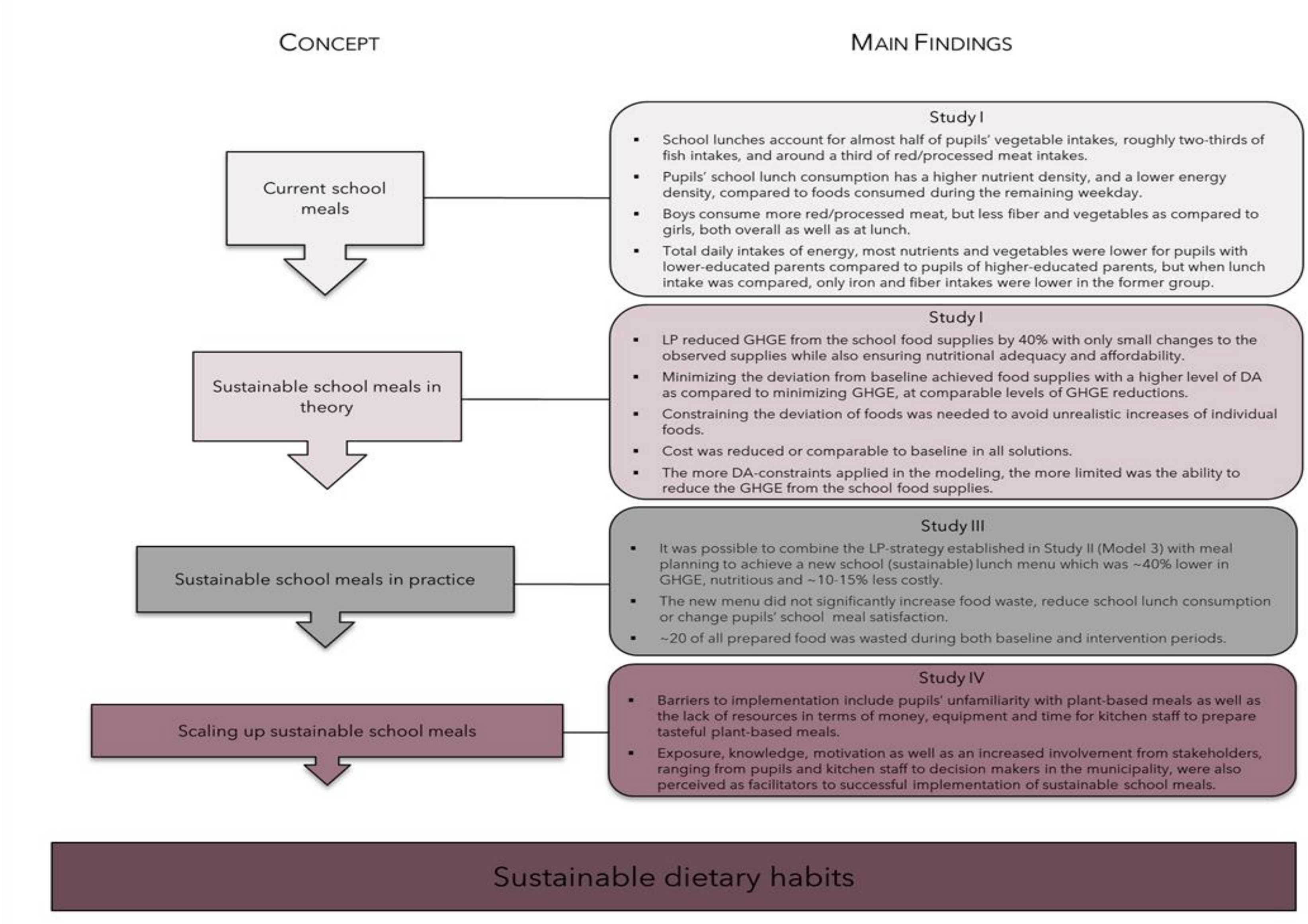


Figure 5.1. *Summary of main findings. LP, linear programming; GHGE, greenhouse gas emissions; DA, diet acceptability.*

5.2 INTERPRETATION

5.2.1 The importance of the school meal to children's diets

Results from Study I showed that pupils' absolute intakes of critical nutrients (e.g., vitamin D folate and saturated fat) align better with the DRVs in the Swedish School meal standards compared with the assessment of children's school lunch intakes in 2003 (184). However, Study I showed that pupils' intakes of energy and nutrients did not fully meet these recommendations. On the other hand, Study I compared average intakes against RIs which are meant to cover dietary needs of ~97.5% of primary school pupils, thus average intakes should not be expected to be as high as the DRVs indicated in the Swedish school meal standards. Findings from Study I showed that the nutrient density was higher, and the energy density lower, at lunch compared to foods consumed during the remaining weekday. This may be reflecting the combined effect of the school meal law introduction in 2011 and the fact that most municipalities in Sweden today tend to plan their school lunches in accordance with the school meal recommendations (174,205). These findings mirror those of researchers exploring school meals in the UK. There, school meals planned in accordance with food-based standards were found having a higher nutrient density than packed lunches prepared at home and consumed in school (206–210). In contrast, the nutrient density of Canadian pupils' dietary intake was lower during school hours as compared to intakes during non-school hours (211). A wide variation in school-food budgets and in adherence to nutrition guidelines across Canadian schools (211) could explain why these findings differ from those of Sweden and the UK. In summary, these findings emphasize the value of having laws and national recommendations for school meals, but perhaps also highlight the importance of having well-established follow-up systems for such laws or guidelines at national level that can ensure equal access to nutritious school meals for all children.

In Study I, the school lunch played a significant role for pupils' vegetable consumption by providing nearly half of their total daily intakes. This is an important finding considering the significant health promoting effect of vegetable consumption (212). The finding also aligns well with previous research from Canadian (211), Danish (164), and American (165) school meal contexts. In the two latter countries, lunches served in school were shown to provide significantly greater amounts of fruits, vegetables and fish than lunches packed from or consumed in the home environment. These results underscore several important aspects, the first being that school meals, may be important for children's possibilities to uphold health promoting diets, especially if supported by food/nutrient based guidelines. In connection to this, such school meals, if being provided to all children at no cost, could also help to decrease social inequalities in dietary intake. Socioeconomically disadvantaged children have been shown to be less likely to consume fruits and vegetables overall; something that has been observed in Nordic settings (213–215) as well as in other high-income countries (216). This was also evident in Study I, where pupils of lower educated parents had significantly lower total daily intakes of vegetables than pupils of parents with higher levels of education, yet at lunch, no significant differences in mean vegetable intakes were seen between the two groups. School meals may thus hold a significant potential to level out some of the well-known diet-related inequalities linked to education. Similarly, a study from Norway (where school meals are traditionally not provided) explored the effects of offering free school meals. The study showed that consumption of healthy foods such as fruits and vegetables increased as the meals were introduced, especially in socioeconomically disadvantaged pupils (217). School meals have also been shown to narrow socioeconomic gaps in dietary intake in countries such as the UK (218,219), Japan (220) and the United States; a country where children included in the National school food program (based on parental income) have been shown to consume around 40% of their daily energy from the school lunch (221). These findings highlight the instrumental role that school lunches can play in compensating for lower dietary quality and/or quantity in the home environment. And this is a critical aspect to consider in the context of school closures during crisis such as the ongoing SARS-CoV-2 pandemic. According to the United Nations' World Food Programme, nearly 370 million children in 199 countries were missing out on their daily school meal during the school closure peak in April 2020 (222). Although the full long-term implications of these events remain to be assessed, a recent report suggests that school closures could have disproportionally reduced the dietary quality of children from low-SES households in the UK (223). In summary, these findings emphasize the potential of school meals to level out social inequalities in dietary intake and their importance in promoting the intake of healthy and nutritious foods across children of all socioeconomic groups

Findings from Study I also revealed differences in the dietary intake of fiber, red/processed meat and vegetables between boys and girls. Boys were found to have higher energy-adjusted intakes of red/processed meat but lower energy-adjusted intakes of dietary fiber and vegetables than girls both overall and at lunch explicitly. These dietary differences are also seen in the Swedish adult population (224) as well as among European adolescents (225) and adults (226). The results thus support gender theories associating the consumption of meat, and fruits and vegetables with masculinity and femininity, respectively (227). They also highlight plausible inequalities in exposure to diet-related morbidity seeing that diets high in red/processed meat are suggested to increase the risk of developing certain types of cancers while diets low in unprocessed and fiber-rich vegetables decrease the risk (228). On the other hand, a low meat intake among females could also increase the risk of iron deficiency anemia. The observed dietary differences among males and females could thus have implications for gender inequalities in health, which need to be further studied. Understanding and considering the sociological pathways underpinning differences in dietary intake between the sexes is therefore likely to be key when designing health promoting initiatives.

5.2.2 Food supply, consumption and food-based recommendations

As mentioned, adherence to national guidelines for the planning of school meals (174) seems to be widespread among municipalities in Sweden (205). Not surprisingly, the baseline food supply in Study II and III met food-based recommendations for fish, fruits and vegetables as well as red/processed meat. However, although the school lunch is providing almost half of pupils' total daily intake of vegetables (including pulses) (**Figure 4.4**), their total average daily intake of fruit and vegetables ranges from 197 grams in boys 11-12 years and 247 grams in girls 14-15 years (229), thus well below the Swedish weekly target of 500 grams of fruits and vegetables per day (183). Similarly, pupils' total daily intakes of red/processed meat, of which a third is provided by the school lunch (**Figure 4.4**), ranges from 71 grams in girls 14-15 years and 118 grams in boys 14-15 years (229), which exceeds or nearly exceed the Swedish weekly population target of maximum 500 grams of red/processed meat (183). Children's inadequate consumption of these may not only have negative implications for health but may also be seen as problematic from an environmental sustainability perspective. Addressing these challenges through the Swedish school meal system by serving lunches that meet both health and environmental goals while also being acceptable could be offer one part of the solution. However, shifting diets to meet both human and planetary health demands is a challenge likely to necessitate urgent and comprehensive solutions that consider all food consumption. Besides the school lunch, it may also be important to explore optimal solutions relevant for the overall diets of Swedish adolescents. Such optimizations could be used to inform the development of food-based recommendations (230) that could guide adolescents in their dietary choices both within and outside of school. However, although LP is acknowledged as a dynamic and vigorous approach to translate nutrient recommendations into realistic food choices (230), the results from the modeling would thus need to be processed together with other scientific evidence and other legitimate factors before devising food standards for the general population or schools.

5.2.3 Food group patterns of optimized solutions

The optimized food supplies in Study II and III were predominantly characterized by increased amounts of pulses, potatoes, and cereals and decreased contributions of animal products such as red meat and dairy. These shifts align well with findings from previous studies which have optimized diets to be more climate friendly, nutritious and acceptable (94,110,112,116,141). Despite these shifts, the modeled solutions in Study II and III did not exclude entire food categories and were thus always omnivorous. The solutions were, in fact, to a considerable extent subjected to alterations occurring within food groups rather than between them. This is similar to other research (121,139,147,231–233) where diets optimized to be acceptable, nutritious, and more climate friendly were attained partly through substitutions within food categories. In two examples (231,232), the total contribution of meat products to the diet was actually increased as a result of the modeling. However, the share of red meat decreased within its associated food category while other less GHGE-intense animal foods (e.g. poultry) increased. Similarly, Vieux et al. (233) also observed these intra-food group substitutions, although within- and between food group shifts by country and/or sex, indicating that shifts towards more sustainable diets will vary for different contexts and subgroups in the population (further discussed under section 5.3.4).

The optimized food group patterns of Study II and III to some extent also mirror that of the healthy reference diet recommended by the EAT-Lancet Commission (8). For example, the optimized food supplies contained comparably low amounts of red meat, poultry, fish and eggs but large amounts of vegetables and pulses in order to provide a nutritious and climate-friendly school lunch menu. However, unlike the EAT-Lancet diet, the optimized school food supplies contained considerable amounts of potatoes. As opposed to other staple crops such as wheat and maize which today dominate the share of daily caloric intakes globally, potatoes constitute a central staple-crop in Sweden. Since potatoes were high in the baseline food supplies, they were also dominant in the optimized supplies, which were modeled to be as similar as possible to baseline, i.e.: acceptable. On the other hand, the LP-model used in Study III did not favor fruits and certain vegetables (such as tomatoes, cucumbers and lettuce) to reach nutritional and climate objectives. Fruits are generally not served extensively in Swedish school canteens and were thus not available in large amounts in the baseline food supply nor in the optimized solution. Furthermore, fruits and certain vegetables may be less effective in the per-calorie supply of required nutrients at a low CO_2eq-cost as compared to other foods such as potatoes and pulses that were both increased in the optimization. This mirrors research showing that, diets optimized to meet nutritional constraints tend to increase fruits and vegetables more than diets that also consider environmental sustainability (116,127). The increased inclusion of fruit and vegetables into a diet can in fact lead to higher environmental impacts (87,89,90,234), or be less effective in reducing them (231). Self-selected diets deemed to be healthier (95,103) and diets optimized to meet nutritional constraints only (139,152) have also been shown to have higher climate footprints. These aspects add to the challenges in defining the sustainability of diets/food supplies. It is therefore important that holistic approaches (such as linear programming) are employed, where plausibly conflicting and synergistic dimensions of diet sustainability can be balanced to find an optimum pathway.

5.2.4 Synergies and trade-offs in the modeling of sustainable school meals

In Study II, four different pathways were explored for the optimization of the school food supplies. The minimization of GHGE in Model 1 achieved the greatest reductions in GHGE (up to a 95% reduction). However, it was only possible to reach such reduction-levels when no acceptability constraints were applied. The ARDs obtained were also the highest in the solutions of Model 1. This modeling pathway was therefore judged unrealistic from a consumer-acceptability perspective. Other researchers have encountered similar results (110,112,113,154,235). For example, Macdiarmid et al. (110) were able to model a 90% reduction in GHGE of UK average diets, while still meeting nutritional requirements. There, entire food groups were excluded or reduced, and large deviations from the observed dietary patterns resulted, thus limiting the acceptability of the modeled diets. As in previous research (110,112–142,144–154), Study II thus also explored the option of minimizing the deviation from observed food supplies (Model 2-4) and progressively constrained GHGE to achieve more realistic climate friendly solutions. Model 2 partly achieved this goal, but high deviations (~+1000%) of some individual foods made the solutions impractical for the school meal context. Like in other diet optimization studies that have minimized the departure from current dietary patterns while constraining environmental footprints and/or nutrients (112,114,117–119,125,128,132–134,137,139,140,146,151,152), Model 3 additionally constrained the deviation of food items to further approximate DA. This approach avoided extreme deviations in single foods and was therefore judged appropriate for the optimization procedure in Study III.

The last suggested pathway in Study II (Model 4) also constrained food-group ratios. This is rarely implemented in optimization studies although a few other researchers (113,126,144,146,152) have implemented such constraints to achieve higher degrees of DA in their optimized diet-solutions**.** However, choosing which food-group ratios to constrain is often based on subjective judgement and may risk missing non-obvious interrelationships between food groups that are important for DA. Similar to innovative diet-models developed by researchers in the Netherlands (231), Model 4 was designed to capture these (sometimes) hidden dynamics that may be of importance to plan an acceptable school food supply by controlling of all possible ratios between food groups. On the other hand, the application of food-group ratio constraints also limited Model 4's capacity to reduce GHGE compared to the other models of Study II. This highlights an important trade-off and challenge in maximizing diet preference and reducing GHGE simultaneously, which was also experienced in the Dutch study (231) and other research (94,112,112,116,124,129,139,148,152,154,235). However, findings from Study II and previous research (94,112,124,129,139,148,152), indicate that the environmental and DA dimensions of diet sustainability are compatible until reaching a 30–40% reduction in food-related GHGE. This trade-off is likely to persist if current dietary preferences and food production systems remain unchanged.

The affordability of sustainable diets is also an important aspect to consider. Similar to what others have found (110,112–114,121,142,149,154), the cost of the nutritionally adequate, GHGE-reduced and acceptable school food supplies in Study II and III either decreased or was comparable to baseline values. This synergy is likely to be relevant to the context of school meals, which are financed by municipalities that have limited, pre-defined budgets for their public sector meals.

5.2.5 Sustainable school meals in other countries

To date, initiatives aiming to model and/or introduce more sustainable school meals or other public meals in practice are scarce. However, a few sophisticated optimization techniques have been applied to design nutritious and environmentally friendlier lunch plans for schools (115,142). In the first example, a GHGE-reduced school lunch plan for Spanish primary schools was designed to accommodate cost constraints, 15 DRVs, and cultural habits (i.e. measures to ensure the inclusion of a first course, second course and side dish in every meal). Unlike our approach, some of the constraints were introduced as soft constraints, meaning that the optimized solution did not have to meet these limits by exact numbers. Instead, the optimization algorithm minimized the deviation between the optimized quantities and the upper and/or lower limits of the constraint(s) as part of the optimization function. This approach to designing school lunch plans resulted in GHGE-reductions of around 24% and cost reductions of approximately 15%. The GHGE-reductions achieved through this approach were smaller compared to those achieved in Study II and III. This may be explained by the fact that the GHGE-constraint in the Spanish study was not implemented as a hard constraint, thus reducing the "leverage" of the constraint to achieve the desired target. Since some of the nutritional constraints were also modeled as soft constraints, not all of them were met in the optimized menus. This was especially true for calcium and vitamin E. Furthermore, the modeling was made to find the optimal composition of dishes (deemed as culturally acceptable) rather on the optimal combination of individual food items. Hence, the flexibility of the algorithm to change the decision variables given the chosen constraints becomes more limited. In the second example, a similar optimization procedure was performed for finding optimal 4-week lunch plans for primary school children in Italy. There, integer linear programming was used to accommodate 7 DRVs (142). Cultural dimensions were also considered, including measures to ensure an appropriate sequence and variability of dishes as well as constraints limiting the contribution of specific food groups to the 4-week menu. These constraints could to some extent be comparable to the efforts of the meal planner in Study III. The model either minimized food-related GHGE or the water footprint (WF) of the menu, achieving reductions of 20 to 40% in GHGE and 20 to 35% in WF. The reductions in GHGE mirror the levels achieved in Study II and III. However, cost was not explicitly considered (or calculated) and only 7 DRVs were met as opposed to 27 in Study II and III. These examples both have the advantage of optimizing menus, based on a set of dishes deemed to be culturally acceptable, without the additional requirement of a meal planner. But although both studies (115,142) exert promising approaches to mathematically designing sustainable school meal plans, the optimized menus were never tested in practice. Hence their acceptance by pupils remains unknown as opposed to the optimized menu in Study III.

Three examples of more practical initiatives may be found in Germany (236), Finland (237) and Belgium (238). In Germany, comprehensive efforts to lower the carbon footprints from school meals have been made through the provisioning of more vegetarian options (236). The extent to which this initiative has been successful is, however, unknown as it currently lacks scientific evaluation. Comparability to the work of this doctoral thesis is therefore limited. Introducing a weekly compulsory vegetarian day in Finnish schools resulted in reduced school lunch participation, less consumption, and increased plate waste (237). Nevertheless, acceptance of the vegetarian meals was more or less the same as for other meals after one semester. Similarly, an evaluation of the "Vegetarian-Thursday", applicable to all Belgian public meals, suggest no difference in acceptance (measured as plate waste) between vegetarian and other foods when evaluated among primary school pupils two years after its introduction (238). The findings from these initiative differ from those of Study III and another recent intervention (232) in the sense that the acceptance of the menu changes were observed after a longer period of time despite the lack of measures or attempts to certify meal acceptability. The observed acceptance after a longer period of time may reflect the fact that acceptance of new foods tends to increase with increased exposure (239). This was also highlighted as a facilitator to successful implementation of sustainable school meals (further reading in next section).

5.2.6 Barriers and facilitators to sustainable eating

To date, most research exploring barriers and facilitators to sustainable eating has been performed on adults. For example, a lack of general information about plant-based foods and a lack of knowledge about how to prepare them have previously been identified as barriers to adopting plant-based diets among Australian (240,241) and Finnish (242) adults. This mirrors findings from Study IV, where both pupils and kitchen staff discussed increased knowledge of why and how to eat (and cook) more sustainably as a potential facilitator to plant-based food acceptance. However, findings from Study IV also suggest the possession of an in-depth knowledge about these aspects might not be the most important facilitator to successful implementation of sustainable school meals. Pupils and kitchen staff highlighted the undesirable taste of vegetarian meals as a central barrier to the acceptance of plant-based eating in schools. This barrier reflects previous research where the perceived inferior taste of plant-based foods has been identified as a barrier towards adopting a more plant-based diet among Australian (240) and Danish (243) consumers. For the Danes, this barrier was predominant in groups with the highest levels of meat consumption. The perceived enjoyment of eating meat (as opposed to the perceived dislike of plant-based foods) has also been found to be an important barrier to consuming plant-based foods (241,242,244). A recent report based on the Swedish school meal context corroborate the importance of taste to the acceptance of plant-based foods (245). Here, pupils also highlighted the food's appearance as a determinant of their food choices; an aspect that has been identified as a barrier of school food acceptance amongst children in previous research (246) and in the FGDs of Study IV.

In the FGDs, both pupils and kitchen staff expressed a desire to be more involved in the development of new menus; something that has been emphasized also by pupils and kitchen staff in other Swedish schools (245). These aspects relate to one of the core components of implementation science, i.e. co-production (247). This aspect connects to self-efficacy among both receivers and providers of a new program, which has been found to be important for successful implementation (247). Research has previously highlighted the potential gains in involving the target group and/or involved stakeholders in the development and implementation of an intervention (248,249). For example, engaging children in such processes has been shown to positively influence aspects such as their consciousness, abilities and motivation (249). In fact, motivation is a facilitator that may be linked to self-determination theory (SDT) (250), which distinguishes between controlled motivation (engaging in health behaviors to e.g. attain a feeling of acceptance, approval or reward) and autonomous motivation (engaging in health behaviors because they align with inherent goals, interests or values). In Study IV, pupils emphasized autonomous motivation as a potential facilitator to fostering plant-based food acceptance and discussed the opportunity for future initiatives to highlight different reasons to why these foods could be beneficial to pupils on a personal level. Research suggests that individuals that engage in a new health behavior due to autonomous motives are more inclined to adopt and maintain the behavior in the absence of external reinforcement and readiness (250–252). Future research could explore children's autonomous motives to adopt more plant-based diets as this is likely to be significant to large scale implementation of sustainable school meals.

Pupils and kitchen staff in the intervention schools (Study IV) also emphasized the involvement of other stakeholders, such as principals and decision makers in the municipality as an opportunity to achieving dietary changes towards more plant-based eating in schools. This is an important aspect to consider since strong leadership support is suggested to facilitate successful implementation of a new program (247), whereas the lack of it has been found to be a barrier to implementation of school-based programs (253). Hence, a transition to sustainable school meals at scale is likely to also depend on dedicated and resolute leadership at both school and municipality levels.

5.3 STRENGTHS, LIMITATIONS AND FUTURE RESEARCH

5.3.1 A nationally representative dietary assessment – usefulness and limitations

Understanding what children consume through representative individual dietary intake data is likely to be important in achieving dietary shifts (55). In Study I, a nationally representative assessment of the importance of school lunches to Swedish children's overall diets was therefore performed. It is the first Swedish study ever to explore this issue in older age groups (14- to 15-year-olds) and by SES. Study I also delivers a basis for a comparison with previous assessments of school lunch intakes in grade 5 pupils (184). The findings of Study I can thus provide an indication of how the performance of the school meal system in relation to guidelines and children's preferences has changed over time.

The original Riksmaten Adolescents survey (176) had a high participation rate. Although minor divergences were observed compared to the general population, the sample is fairly representative in terms of school organization, school size, and parental income, education, and background (176). The RiksmatenFlex tool used for data collection has been validated against interview-administered 24-hour dietary recalls and is shown to provide dietary intake estimates comparable to 24-hour recall interviews (176). However, the dietary data may still be subjected to uncertainties. For example, self-administered 24-hour dietary recalls (used for the first and third reporting day) are limited primarily by aspects related to memory and difficulties in estimating quantities (254). Food records (used for the second reporting day) may instead be limited by unintended reactivity which can result in changes in intakes and reduced consumption on reporting days (254). Furthermore, adolescents may be less interested in giving accurate reports than younger children (255). As in most dietary surveys, the data used for Study I may thus still be limited by some degree of both random systematic error which could have biased the findings (255).

Another general consideration with regards to the dietary data used for Study I is that pupils did only provide dietary information up to three weekdays, from which the mean intake of nutrients and foods was calculated for each individual. Considering that an individual's dietary intake will likely vary from day to day (256), these means may not adequately reflect pupils' habitual intakes at lunch. The uncertainty in extrapolating long term consumption from short term, cross-sectional, dietary reports thus warrants attention. Presumably there is quite a difference between a three-day dietary measurement and a 1-week, or even 1-year, average consumption level—i.e. the extrapolation of an individual's daily intake to a longer term average is likely to be subject to error as a result of unknown within-person variation, variation which will depend on the food item/group being assessed (257). Accounting for these variabilities would be valuable in future analyses of children's school lunch intakes. On the other hand, taking averages over the population of three-day dietary measurements are prone to less error because of the sample size, and because of the design of the study these averages are likely to be good approximations to long term population average diets. Taking averages over the population of three-day dietary measurements may therefore be seen as an adequate approach to provide useful population-based estimates on children's school lunch intakes of relevance to both policy and practice (254).

5.3.2 LCA- and nutrient data: uncertainties and gaps

5.3.2.1 Uncertainties in LCA-data on climate footprints

LP-models are sensitive to the quality of the data used in the model (230). The optimum solution will thus inevitably depend on how updated and reliable underlying input data are. There is extensive heterogeneity in how crops are being produced today resulting in that the environmental impact of the same product can vary up to 50-fold among producers of the same food (86). The footprints can thus vary depending on the producer as result of different production systems, local growing- and/or weather conditions, the year of assessment, the variety of a food being produced, the type of electricity used for production, the level of processing, transport, and the LCA-method used to estimate the impacts. Hence, the LCA-data used for Study II and III are likely to be subjected to a certain extent of uncertainty. The climate footprints used for this thesis should, therefore, be seen as an approximate measure of each product's climate impact and not as exact values.

Furthermore, the system boundaries only covered the impacts up until factory gate. This could be seen as a limitation, however, most LCAs of foods only cover activities up to the factory gate seeing that the main proportion of impacts is generated within this production-frame (86). An example of this is illustrated in **Figure 5.2**.

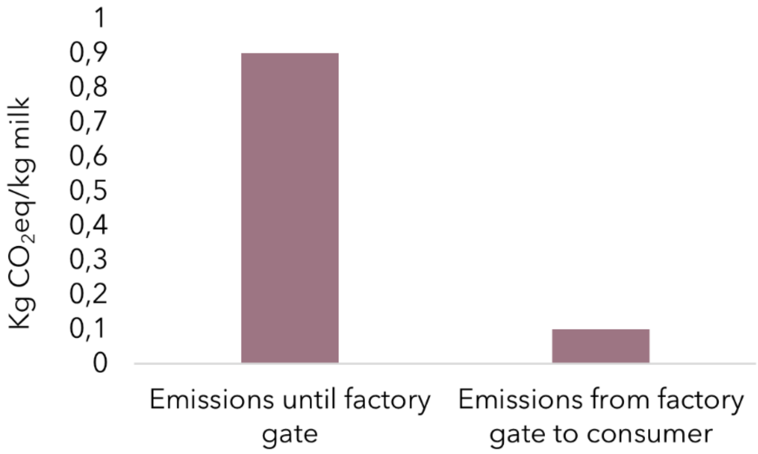


Figure 5.2. *Greenhouse gas emissions (CO_2eq) associated with primary production (until factory gate) and the rest of the life cycle of milk production. (Adapted from Florén et al. 2015 (191)).*

As such, the system boundaries of climate data do not include the impact from food-preparation (i.e. emissions from the energy use in the school kitchens). However, for products such as meat, fish, rice and pasta, the food-preparation was to some extent considered by recalculating what a certain amount of prepared product would correspond to in "uncooked raw material". Different forms of a food have different climate impacts; a food in its boiled form can give lower climate impact/kg of product when water is taken up and the concentration of the food becomes lower, while some foods can have a higher climate impacts/kg of product when prepared due to water discharge. Although Study II and III focused on food supplies (i.e. foods in their raw, unprepared form), the decision variables of optimization were the edible forms of each food in order to ascertain that all DRVs were met. Using yield factors and edible proportions, weights of purchased raw foods were converted into weights of edible foods for the optimization (to account for weight changes occurring during cooking and unavoidable kitchen waste). However, their raw weight, by which they would be purchased, was used by the meal planner/school chef.

Moreover, the LCA-data used for Study II and III did not include impacts from food-packaging. This aspect could be seen as an advantage for this particular research since schools often purchase foods in catering size packs. The LCA-studies in the Climate Database have in most cases considered packaging, which would provide a misleadingly high proportion of packaging per kg of food compared to what a catering size pack would generate. Therefore, several recalculations have been made to existing LCA-data in order to remove the impact of packaging as well as to streamline the climate data with respect to the functional unit. These measures might add another level of uncertainty to the data, although this has only been done to ~10% of the LCA-data sources.

An estimated 80% of the deforestation globally can be attributed to the expansion of agricultural land, to a large extent driven by the increased global demand for food and meat in particular (258). An increased demand for animal products also means an expanded demand for feed, including soybeans (259). The soy-based animal feed is largely being provided by arable and grazing land that was previously rainforest (258). Forests provide a multitude of vital ecosystem services (260). They are essential for the conservation of biodiversity and function as important carbon sinks (260). Terrestrial carbon losses (i.e. potential carbon storage under natural vegetation compared to carbon storage under different agricultural land use types) due to land use change would thus reasonably be important to consider in LCA of foods (261) However, this aspect is not covered by the LCA-data used, meaning that the climate impacts for some foods are plausibly underestimated whereas the contribution of these same to the optimized solutions are likely to be overestimated. This would be particularly true for meat from soy-fed animals. The magnitude of these terrestrial carbon losses are, however, difficult to reliably estimate (191).

The IPCC updated the GWP for methane in 2013 (262), from 25 to 34 (relative to CO_2 having the GWP of 1) over a period of 100 years. The Climate Database used for Study II and III is based on LCA-data applying the former value, which is 27% lower than the latter. This means that the climate impact of the optimized school supplies which contain ruminant meat might have been underestimated. On the other hand, evaluations show that the estimation of GWP as a GHGE-metric is subjected to several uncertainties (263), one of which relates to the fact that GWP values for methane and other greenhouse gases inextricably depend on changing CO_2 concentrations; as the concentrations of CO_2 increase in the atmosphere, the GWP-values of other greenhouse gases do too (264). Moreover, the GWP-approach does not consider the understanding that roughly a fifth of the emitted CO_2 remains in the atmosphere for several thousands of years (265,266). It is estimated that a considerable proportion of the increase in the GWP for methane between the IPCC 2013 report (262) and the IPCC 2007 report (190) is explained by increases in concentration of CO_2 only (264). Methane is a comparably short-lived greenhouse gas with an atmospheric lifetime of approximately 12 years. However, its potency over that time exceeds that of many other gases meaning that it has a GWP which is almost 9 times greater than that of carbon dioxide over a shorter period of 20 years (262). The 100-year time scale used for the climate data may thus risk diluting the shorter-term implications of emissions from ruminant meat in particular. However, employing a 20-year time scale to the GWP of all greenhouse gases (forming the CO_2eq) could instead underestimate longer-term implications of climate change from GHGE with longer atmospheric residence time. Researchers have thus suggested alternatives for comparing different greenhouse gases which avoid the arbitrary time-horizon as used in GWP and that is less biased by progressive changes in atmospheric composition (264,267). What is important to point out is that alternative approaches will result in different weights assigned to greenhouse gases such as methane, which in turn may lead to different priorities in the development of climate change mitigation policies (268,269). The full scope of these complexities stretches far beyond the limits of what this discussion is able to cover, and the aim is not to disqualify GWP as a valuable GHGE-metric.

Instead, the purpose is here to recognize the matter as it adds to the multitude of uncertainties linked to the quantification of climate impacts which should ideally be considered when interpreting outputs from optimizations such as those presented here.

5.3.2.2 Gaps in LCA-data of foods and the importance of coproduction links

In this thesis, the environmental impact of school food supplies was assessed only on the basis of GHGE. Hence, other relevant characteristics of environmental sustainability in the context of diets such as eco-toxicity, land use change, water use, eutrophication, acidification, animal welfare and biodiversity loss were not considered. This is a limitation since different foods vary in their environmental impacts (74); animal products are tend to be the most GHGE-intense while staple crops (for human consumption), generally are the main contributors to freshwater use per kg of food. Biodiversity is also an important factor that ideally should have been considered, especially with regards to the production of fish; a food group that increased in the optimized food supplies of Study II as well as in other optimized diets (111,116,124,127,129,139,147,148,270,271). Being high in bioactive and essential omega-3 (n-3) fatty acids, low in saturated fats, and high in protein, (fatty) fish is also advocated to be consumed as an alternative to red meat (272). These findings and recommendations might not be fully compatible with other environmental dimensions of diet sustainability seeing that 96% of the world's fish stocks are endangered (ranging from moderately exploited to depleted) (273). Hence, current fish production from wild stocks may not be a sensible alternative to turn to for meeting the proposed dietary shifts. Turning to the alternative, fish from aquaculture could be a sustainable option (274), although, this would depend on the mode of production system; even the lowest-impact aquaculture systems can generate GHGE equal to or greater than that of other animal products such as pork (per kg of food) and can additionally contribute considerably to eutrophication (24). Yet, when assessing climate footprints of entire diets, GHGE are suggested to serve as a suitable proxy of other environmental impact categories (9,270,275). Diets with lower impacts for one environmental impact category usually have lower impacts on others (276). A robust database on the variation in food's multiple impacts was recently established by Poore and Nemecek (86). Official data currently only provide global averages for greenhouse gas emissions, land use, acidification, eutrophication and freshwater withdrawals, however these could be used to provide approximate estimates for optimized school food supplies in Sweden.

The applied modeling in Study II and III did not consider linkages between foods (e.g. beef is a byproduct of dairy farming) as done by Barré et al. (114). In their optimized solutions, the amount of meat was reduced to a lesser extent when accounting for the coproduction links milk–beef and blood sausage–pork as compared to models excluding these links. Since wasting of beef that results from milk consumption is neither ecologically nor economically sound, future optimizations could benefit from taking such, and other relevant, co-production linkages into account.

5.3.2.3 Uncertainties in nutrient data

Some uncertainties also apply to nutrient data. Although the Swedish Food Agency's food composition database can be seen as reliable, there may still exist large variations in nutrient content between different varieties of one and the same food (e.g. tomatoes) which may go uncaptured. This can depend on aspects such as where and how varieties of the same food have been produced which in turn relate to soil factors, cultural practices (e.g. plant spacing), season, climatic and light conditions the specific variety being (277) or the particular animal race being bred (278). As the nutrient content of individual foods may differ markedly, individual nutrient values in the food composition database should be interpreted as average values (278).

5.3.2.4 Gaps in nutrient data

There are also some gaps concerning nutrient data. For example, the Swedish Food Agency's food composition database does not contain information on the amino-acid composition of different foods. Consequently, the optimized food supplies have not accounted for this aspect as done by other researchers (129). This may be a limitation since animal products (reduced in the optimizations) in general are considered complete protein sources as they contain an adequate composition of essential amino acids. This is less common among individual plant-based foods which in the optimized food supplies some extent replaced animal foods. Nevertheless, the combination of plant-based foods in a diet can provide all essential amino-acids and a balanced plant-based diet is able to provide protein which is considered complete and of high-quality (182). Moreover, protein quality is less of a public health issue in high income-countries today. Therefore, the dietary changes proposed by the LP-algorithm are not likely to implicate children's protein status. However, it could still be important to fill this information gap if intending to suggest diets or serving menus that will require persistent and significant shifts from animal products to plant-based foods.

Furthermore, the Swedish Food Agency's food composition database does not provide information about the bioavailability of nutrients in different foods, and no additional measures to account for this was made in the optimizations for Study II and III. Iron and zinc could in this regard be nutrients of particular concern seeing that their bioavailability in meat products (reduced in the optimizations) is higher than in e.g. pulses (increased in the optimization) (279). As for iron, animal products are the main source of heme-iron which is the most bioavailable form of iron. Introducing school lunch menus that contain less meat products could have implications for the micronutrient status in vulnerable populations, especially in Swedish teenage girls of which about 30% have low iron stores (280). The extent to which the optimized solutions may be deemed nutritionally adequate may thus not be fully clear, especially since both iron and zinc were active constraints (i.e. amounts meeting DRVs by exactly 100%) in the optimized food list for Study III. Future school meal optimizations would benefit from considering the bioavailability of key micronutrients such as iron and zinc as done by other researchers (114).

Given the uncertainties in LCAs and nutrient data, findings from Study I, II and III should be cautiously interpreted. The highlighted information gaps also provide suggestions for how LCA- and nutrient data sources could potentially be expanded to enable the development of more robust and holistic optimization models.

5.3.3 Future perspectives for school-based interventions

As mentioned previously, Social Cognitive Theory (SCT) builds on the idea that human behavior is determined by reciprocal interaction between personal, behavioral and environmental factors (193). Promoting healthy eating among young people by changing the physical environment in ways so that healthier choices become more accessible and attractive is central to behavioral economic approaches (281,282) which also connect to SCT (193). Increasing access to and availability of healthy foods in general (283), and during school lunch specifically (284), are shown to be important facilitators of healthy eating among young people. One main strength is that the OPTIMAT-intervention approach changes the physical environment of children by making sustainable foods accessible. Dietary decision-making is also determined by dynamic cognitive processes (285). Making a dietary choice first and foremost depend on the brains ability to identify an object as food (286), i.e. a cognitive process that entails the recognition and processing of an external stimulus as a potential object of desire. In response to this recognition, the brain proceeds to executing numerous computations which ultimately determine the decision of eating the food or not (285). This decision will depend on aspects such as timing (the time distance from the previous meal), the extent to which the food has previously generated enjoyment, the extent to which the act of eating the food aligns with health goals, the social context, and if there is a previous habit of eating a food in a particular context. Hence, dietary-decisions result from a cognitive process where sensory, somatic, sociocultural and circumstantial information is incorporated in memory (287). Particular cognitive control systems that in turn interact with metabolic factors (285) have been found to guide dietary decision making (288). These include Pavlovian, goal-directed or habitual control processes which are formed over the continuum of life (within individuals, families, peers or other social constellations) and are influenced by sociocultural heritage (289). Pavlovian (intuitive) systems relate to the learned association between the taste of a food and an immediate positive hedonic response (290) while goal-directed (reflective) systems are the cognitive processes where abstract representations of outcomes guide the decision of whether to eat a food (291). Habitual (intuitive) systems connect to behaviors shaped through the repeated experience of eating a particular food and are predominantly determined by information about the immediate outcome from eating the food rather than abstract representations of outcomes (285). The type of control system that dominates the decision making will depend on the particular setting where the decisions is undertaken as well as the perceived prospective advantages of going for one strategy over another (285).

Taking these important control systems into consideration, the OPTIMAT-intervention approach could be considered as having potential to influence some of these systems. Although only deliberately targeting Environmental factors (as defined by SCT), the intervention-approach may unintentionally also have influenced Behavioral factors of relevance for behavior change though its plausible influence on both Pavlovian and habitual decision-making systems. For example, the implementation of sustainable meals may indirectly have potential to affect children's Pavlovian control systems for dietary-decision making in both the short and long term by providing sustainable school lunch menus optimized to align with pupils' current food preferences. The daily exposure of plant-based foods though menus such as the one implemented in Study III is also likely to influence children's habitual systems, especially if implemented as early as in pre-school. One potential difficulty for the current OPTIMAT-intervention to influence the goal-directed (reflective) control system for dietary decision-making is that it does not include any measures aiming to influence pupils' understanding and knowledge about sustainable eating. According to SCT, both knowledge and attitudes are relevant Personal factors to behavioral change (193). Studies have shown that personal attitudes are strong predictors of sustainable food consumption (preference and choice) which in turn interconnect with knowledge (292–296). School-based interventions targeting children's diets have been shown to be more effective when incorporating educational components in tandem with environmental changes (297,298). For example, Finnish pupils were shown to increase their uptake of a daily vegetarian dish when different educational activities aiming to raise awareness about sustainable eating were implemented at the schools (299). Moreover, findings from a randomized controlled trial (300) demonstrate that the probability of consuming a meat-based meal reduced while the probability of consuming a plant-based meal increased significantly among American college students having received a 50-minute lecture on how food choices affect climate change as well as information about the health benefits of consuming less meat. By incorporating educational components focusing on sustainable development and sustainable diets in particular, an increased understanding of the links between food systems, health and environmental sustainability could be generated. These could translate to positive attitudes towards eating climate-friendly lunches. Interventional approaches that target several factors of relevance to behavioral change may thus be more effective as they are more likely to combine both intuitive (Pavlovian and habitual) and reflective (goal-directed) cognitive processes (301), which in turn could successfully enable pupils to better internalize sustainable dietary patterns. Future intervention studies could aim to explore such approaches.

5.3.4 Diet acceptability – how and for whom?

5.3.4.1 Strengths, gaps, and options

One of the main strengths of LP is that it is able to provide one optimal solution to a complex diet problem where several (sometime conflicting) demands are being met. But this strength may also be considered one of its weaknesses. Delivering one "acceptable" solution may imply minor dietary changes for some individuals but larger (and potentially unrealistic) changes for others (127,132,302). For example, male pupils are (when faced with optimized menus such as the one developed for Study III) likely to face larger absolute and relative changes to their consumption of red/processed meat as compared to females in Swedish primary schools due to their different current consumption levels (as seen in Study I). Consequently, the optimized school lunch menus risk being less acceptable to some subgroups of pupils, which could have implications for food waste and consumption. Study III cannot assess such potential differences in acceptance since food waste and consumption (before-after) was compared on school level. Future intervention studies could therefore also explore the possibility of taking an individual approach to assessing food waste and/or consumption. Such knowledge could be important as for identifying particular subgroups in a school or municipality that might be less accepting of menu-changes and thus indicate which groups that might need extra support in achieving the necessary dietary shift.

So far, previous optimization studies have focused on addressing the acceptability of optimal diet solutions exclusively from a mathematical perspective. In contrast, Study III was designed to provide a practical test of how optimized school lunches would be received by a wide (and heterogenous) range of consumers. This is one of the main strengths of this thesis. Another important strength is that the developed LP-approach to designing sustainable school meals (Study II) allows for school meal menus to be optimized according to specific conditions (preferences, resources, skills etc.) of a particular context. Although the optimized menu implemented in Study III is likely to be relevant only for the three schools subjected to the intervention, the method per se could be transferable to other contexts.

The LP-approaches of Study II and III did not include foods that were not already present in the baseline food supplies. A limitation of the LP-models in Study II and III is thus their lack of room for innovation. There are many new, climate friendly meat/dairy replacements emerging on the market, which are also fortified with nutrients such as vitamin B12 and calcium, i.e. nutrients that tend to be insufficient in plant-based diets (303,304). Including these foods in the optimization of new menus could be an alternative path to providing climate- and nutrient efficient foods with favorable sensory traits. Researchers in the UK (127) allowed for new foods to be included in some of their optimization models while allowing currently consumed foods to both increase and reduce in amount. These models were able to achieve greater GHGE-reductions compared to models that only changed the amount of foods currently consumed. Yet, such modifications could potentially also result in more pronounced dietary changes, risking to negatively impact children's more pronounced sensitivity to new foods (132,148). On the other hand, pupils discussed plant-based dishes that resemble animal-based foods in an overall sense as an opportunity to increased plant-based food acceptance (Study IV). Future optimizations could therefore explore the effects of also including such foods in the modeling as way to deliver nutritious, climate friendly and acceptable school lunches. However, the science base for the potential health impacts of consuming plant-based processed novel meat alternatives might first need to be expanded due to concerns over e.g. their sodium content (305).

5.3.4.2 Maximizing similarity to unacceptable school meals

Study III employed the LP-strategy from Study II (Model 3), where the TRD from the baseline food supply was minimized as a proxy for DA. This approach also proved to be able to achieve a more similar food supply than those minimizing total CO_2eq at comparable levels of GHGE reductions (as seen in Study II). Although the new menu tested in Study III was judged acceptable, approximately 20% of the prepared food in all three schools was wasted during both the baseline and the intervention period, respectively. The same was observed for all schools partaking in the second OPTIMAT-intervention (232). The findings from the online questionnaire on school meal satisfaction performed in Study III further revealed a relatively low satisfaction with school meals during both the baseline and the intervention period; something that pupils' statements from the qualitative findings in Study IV also corroborate. In line with these findings, results from Study I also indicated a low satisfaction with school meals amongst pupils seeing that approximately one third of pupils skip at least one school lunch a week. Similarly, previous findings on the Swedish school meal context demonstrate that older (usually pupils in grade 5 and above who are permitted to leave the school area during the school day) regularly omit the school lunch (306,307). Based on the multiple methods and data sources across Study I, III and IV and other research these findings indicate that there seems to be a general and comprehensive dislike of school meals amongst Swedish primary school pupils. This would mean that an approach such as OPTIMAT (as it is designed now) is likely to fail in providing a fully sustainable solution despite not causing an increased food waste as observed in Study III. The applied LP-approach is designed to offer new (nutritious, climate friendly and affordable) school lunch menus which are as similar as possible to the ones currently being served. However, if current menus are not widely accepted in the first place, new menus are likely to also struggle in reducing food waste in line with priorities of the Agenda 2030 (72), the Eat Lancet Commission Report (8) and other proposed action-plans for sustainable development (6,56,73,75,76). This is an important limitation of the current approach.

5.3.4.3 Options for delivering sustainable solutions in the school meal system

What methodological options are then available if aiming to design future school lunch menus that are nutritionally adequate, that help to keep global temperatures below a 1.5-degree increase above pre-industrial levels, and that also *help to reduce* avoidable food waste? Similar to the LP-models used for Study II and III, other diet optimization studies have also mathematically operationalized DA by controlling the change of food items (referenced in section 5.2.4). Researchers have also constrained the deviation of food groups in different ways (112,114,139,140,147,152). Such constraints were not included in any of the optimizations applied in Study II and III but could be a valuable option to consider for future optimizations of school meals. For example, an unlimited increased absolute amount of a food group such as vegetables (including pulses and many nutrient-dense foods with a low energy density) in a school lunch menu would potentially require for children to increase their total intake of these foods in order to generate a feeling of satiety. This would likely require more time for consuming the school lunch and could thus become problematic in the school meal context, where many children already have less than 25 minutes to consume their lunch (308). In fact, qualitative findings show that the time-aspect (sometimes perceived as insufficient) may already be a reason for food waste (309). Food group constraints could also be useful to meet kitchen staff's concerns about handling leftovers from mixed dishes with pulses that they perceived as less appropriate to save for another occasion (highlighted by kitchen staff inStudy IV).

But these additional constraints would likely not overcome the challenge with pupils' apparent general unacceptability of the school lunch. In order to tackle this difficulty, one might first need to problematize another principal commonality among diet optimization studies. To date, constraints imposed to operationalize DA are in principle based on the researcher's understanding and expertise about current food preferences. Although likely to be valid, these decisions (e.g. to allow a certain limit for the RD of individual food items) may to some extent be considered arbitrary and could thus potentially deliver results that are less optimal from a DA-perspective. On the other hand, this approach could have some advantages in the context of school meals where the LP-model could be re-run and adjusted (e.g., by changing the food item/food ratio constraints) according to the context-specific conditions and demands of the meal planner. This iterative approach was recently explored in a second OPTIMAT-intervention study (232). In this study, a general linear constraint was first applied for the max/min allowed deviation of all individual foods of the baseline food supply. However, based on experience from the first intervention (Study III), tailored constraints on e.g. potatoes were also applied. After the first round of optimization, additional constraints were specifically applied to the RD of some foods following suggestions from the meal planner, after which a new optimization was performed before planning and testing the new menu. This approach enables an iterative procedure in which the meal planner is involved in the making of these methodological decisions. The vast understanding that these individuals have regarding the dynamics between school food standards, the overall preferences of pupils and the capacity (time/resources/skills) of kitchen staff might be difficult to fully replace by a mathematical algorithm. However, a limitation to this iterative approach is that it more or less fully relies on the assumption that the meal planner's knowledge and perceptions are validly reflecting the true context-specific conditions. Furthermore, the process is considerably time-consuming, both for the optimizer and the meal planner.

A recently developed method identifies the healthiest diets in a population while avoiding potential issues of subjectivity (310). Based on data envelopment analysis (DEA), nutrient benchmarking is performed to calculate healthier diets. The goal of DEA is to identify existing "efficient diets" in the population, i.e. diets that for a specified level of unfavorable nutrients contain the highest (relative to all other diets) level of favorable nutrients or vice versa. Data envelopment analysis maintains natural interrelationships between food groups in a non-arbitrary manner as new diets are based on a linear combination of existing ones rather than single food items. Applying this approach to the school meal context could potentially be appropriate as for delivering nutritious school meal-solutions of higher acceptance. An alternative course of action would be to establish a data base containing "popular" dishes defined by pupils themselves, on the basis of knowledge of meal planners and kitchen staff, as well as through evaluations of waste/consumption measurements. The DEA-approach would identify several combinations of popular dishes (over a chosen period) being efficient with regards to health and environmental priorities following which menus could be calculated based on the minimum deviation between the current combination of dishes of a particular school and the efficient combination of dishes with regards to nutritional and GHGE priorities. This would essentially imply "picking" the healthiest and most climate friendly combination of dishes that also resembles the current combination of dishes the most in terms of composition. Exploring the feasibility of applying this approach in the school meal context could provide an opportunity to more objectively integrate pupils' existing food preferences into the mathematical modeling. This approach is also likely to be less time consuming, especially if developed into a user-friendly automated application that can be integrated with municipalities' existing menu planning and procurement systems.

5.3.4.4 Diet acceptability from a broader perspective

The mechanisms underpinning food consumption choices are complex and challenging to fully grasp (311). The acceptability of a school meal menu is likely to not be determined exclusively by the fact that it contains a combination of popular dishes. To date, research on food intake has focused principally on homeostatic and hedonic control processes (287). However, as touched upon in section 5.3.3, decision to eat a food and how much, results from a cognitive process which entails the incorporation of different inputs in memory (287). Recent research highlights the importance of memory to eating and how the memory of a recently eaten meal may influence the future eating behavior to a greater extent than other control processes (285). The representation of previous food experiences may thus also play an important role to pupils' meal acceptability. Understanding and harnessing these (less obvious) dynamics fully with LP might not be possible but would potentially require the use of other techniques such as e.g. Bayesian statistical models, Markov Chain Monte Carlo methods or the application of neural networks (i.e. artificial learning processes).

If moving slightly away from exploring the technical potentials of mathematical models, there may also be a need to study and more deeply understand pupils' food preferences and attitudes towards the school lunch to succeed with successful implementation of sustainable school meals. Study IV partly provides insights to some of these aspects. Here, sensory factors such as taste, the food's appearance and recognition were discussed as important factors to pupils' food choices. Similarly, previous research demonstrate how the lack of availability and variety of preferred foods (312) and undesired aesthetics of foods (246) may act as significant barriers to pupils' school food acceptance. The understanding of food acceptance is likely to be incomplete without consideration of context (313). Hence, we also need to obtain an in-depth understanding about other aspects of the school lunch (experience), which might influence both consumption and waste. Besides taste, findings from Swedish primary schools show that time, environmental factors (noise levels and cleanliness) as well as social aspects (e.g. being allowed to sit and socialize with peers) are also important aspects of pupils' school meal experience that they feel need improvement (309). These are aspects that fall outside the methodological scope of OPTIMAT as a method. However, to fully succeed with implementation of such types of interventions, these aspects are likely to also deserve consideration.

Achieving a sustainable food future is likely to also necessitate holistic approaches that link consumption with production. One potential difficulty for Sweden in increasing intakes of pulses and cereals (reflecting dietary shifts suggested by the LP-models in Study II and III) is the country's current reliance on international trade for supplying these foods. Nearly half of all consumed food in Sweden is imported and just about half of that consists of fruits, vegetables, bread, flour and grains (314). As for the supply of pulses in Sweden, almost all relies on imports from climate vulnerable countries such as China and Canada (315). These are countries that could potentially struggle in producing the same amount or more of these foods under future climate change conditions. Hence, the features of the current import-dependent food supply pattern in Sweden would plausibly not be able to meet an increasing demand of such foods. Would it then be sensible to instead expect local production to fill the gap between the food pattern of current diets/food supplies and those of optimized solutions? Recent analyses suggest that there is potential for Sweden to increase domestic production and consumption of pulses (314,316). But for this to be realistic, areas suitable for growing pulses would need to be vastly expanded, and investments in e.g. the breeding of suitable crop-varieties, in machinery and a training of growers would also be crucial (316). Future optimizations could explore the potential to incorporate dimensions of "acceptability" that also consider prerequisites for both domestic and global production under several plausible policy and climate change scenarios.

6 OVERALL CONCLUSIONS OF DOCTORAL THESIS

This doctoral thesis presents a holistic research effort exploring how sustainable dietary habits can be promoted through the school meal system. It combines findings from national dietary data, context-adapted mathematical modelling as well as intervention and implementation research components. This work shows that the Swedish school meal system holds substantial potential to foster health-promoting and nutritious dietary habits in children, but also to mitigate sex and social inequalities in dietary intake in the long term. The findings also confirm the practical applicability of implementing nutritionally adequate, affordable and climate friendlier school meals based on linear optimization, which do not significantly increase food waste, or change pupils' consumption of, or satisfaction with, school lunches. The combined optimization-interventional approach was feasible to implement in the Swedish school meal system and could plausibly also be transferable to other public sector meal systems that aim to procure and serve more climate friendly meals. However, automated solutions might first need to be developed in order to disseminate this approach at scale.

The potential benefits to the climate are important to emphasize: if each school lunch served in Sweden today contained 400 g less CO_2eq (corresponding to the ~40% reduction achieved in the schools included in this thesis), this would correspond to ~80,000 tons less CO_2eq emissions per year, which is equivalent to the yearly average emissions generated by approximately ~50,000 cars in Sweden. The potential for short-term reductions in GHGE would thus be substantial. This school-based approach also has an important long-term potential to reduce GHGE from diets if successful in establishing sustainable dietary habits that track into adulthood. Additionally, there could be a strong signaling effect of sustainable school meals, which could contribute to changing societal norms around foods and diets.

The observed affordability of nutritionally adequate and GHGE-reduced lunches is one important synergy that is likely to be of value to Swedish municipalities operating on limited, predefined budgets for their public sector meals. The findings of this thesis also highlight trade-offs between consumer-acceptability and climate priorities, but these are likely to become less pronounced in the future as climate-friendly foods become more accepted by pupils and the wider population. Findings across several of the studies highlight an apparent general dissatisfaction with school meals among Swedish primary school pupils. Determinants of this dissatisfaction would need further exploration before bringing this type of optimization-interventional approach to scale while also reducing food waste.

Although the optimized school lunches were implemented with no undesirable effects on acceptability, hurdles to scaling up may still exist. Successful implementation of sustainable school meals may depend on overcoming barriers related mainly to pupils' unfamiliarity with plant-based meals, sensory factors, the lack of motivation and participation of stakeholders such as pupils, kitchen staff, teachers and principals in the change process, and knowledge gaps among both pupils and kitchen staff. Successful implementation of sustainable school meals could thus be facilitated by gradually introducing pupils to plant-based meals, considering the taste, naming and aesthetics of dishes carefully, and by promoting increased stakeholder involvement. Approaches that incorporate educational components and training may also be valuable for promoting children's motivation and abilities to internalize sustainable dietary patterns as well as for strengthening kitchen staff's capacities to deliver palatable, appetizing, plant-based meals.

In summary, this field of research could be improved by:

- Regularly collecting national dietary data on children's diets to better understand their current preferences as well as how and why their eating habits might be changing over time.
- Developing more robust and holistic optimization models in which new foods, nutrient bioavailability considerations, co-production links, other environmental impact categories and a broader range of DA-constraints are considered simultaneously. The quality and scope of LCA- and nutrient data is likely to be important in this regard.
- Developing automatized linear programming tools that can be integrated with existing digital menu planning and procurement systems.
- Developing optimization models that also consider national food supply patterns (domestic vs. imported supply) as well as different policy and climate change scenarios.
- Exploring barriers and facilitators to children's general school meal acceptance in depth, including research to understand children's autonomous motives to adopt more plant-based diets.
- Exploring the potential and effects of incorporating educational components and training activities in combination with serving optimized school lunches.

7 CONCLUDING REMARKS

While highlighting some potential research gaps, it is my hope that this doctoral thesis offers new and important insights into how integrated methods and actions could help to foster sustainable dietary habits in children and thus contribute to fulfilling international agreements on climate change and sustainable development. Change is needed at all levels—sustainable school meals could provide one promising pathway to achieving sustainable dietary habits in the young generation of today and in the future by changing societal norms around food. Yet, this type of change will likely need to be accompanied by a mix of other comprehensive behavior change interventions, bold policy reforms as well as extensive private sector engagement in order to secure both human and planetary health needs. The ongoing SARS-CoV-2-pandemic has demonstrated the capacity and willingness of governments to take powerful action in times of emergency. Equally important, this global crisis has demonstrated the wide-scale willingness of communities and the private sector to support these actions and adapt to protect the health and lives of those most at risk. This inspires hope and trust that timely and joint responses to the global crises of climate change will take place, while at the same time ensuring that all people around the world have access to sufficient and nutritious food—today and in the future.

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***

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SUPPLEMENTARY MATERIAL

Supplementary Table 1. Summary of reviewed optimization studies.

Reference, Author, y, geographic area	Type of dietary data	Type of optimization	Method for implementing DA	Key findings
110. Macdiarmid et al. 2012 UK	National Diet and Nutrition Survey (NDNS) 2008-2010	Linear programming	1. The amount of each food was constrained by an upper or a lower limit. 2. Upper and lower weight limits of individual foods in the model were adjusted until the quantities of food items could be combined into a weekly menu. 3. Constraint on cost.	If not considering DA in the modeling, diets consisted of few foods in unrealistic amounts. Adding DA constraints increased the diversity of the diet but was not able to reduce GHGE from the diet as much (36% vs. 90%).
112. Perignon et al. 2016 France	The second National Individual Survey of Food Consumption (INCA2) 2006-2007	Linear programming	1. Minimization of total absolute departure between the observed and modeled diets, at both the food item and food group level. 2. The total mass of the optimized diet limited to between 80% and 120% of the current intake. 3. The energy content of the optimized diet was constrained to the mean energy content of the current diet. 4. The food item, food group and food subgroup amounts constrained to <90^{th} percentile of current intake levels. 5. Constraint on cost but not defined as a DA-component.	The GHGE from diets could be reduced by 30% while ensuring nutritional adequacy and while deviating moderately from the current diet at the food group level, compared to models only meeting nutritional recommendations, at a comparable cost. Combining both DA and nutritional constraints at GHGE reductions over 30% was not possible. Such GHGE reductions either compromised nutritional quality or required major departures from the observed diet, which in turn compromised DA in order to ensure nutritional adequacy.
113. Donati et al. 2016 Italy	Dietary information was collected from 104 high school students using 7-day dietary records	Multi objective linear programming	1. Food consumption frequency constraint applied. 2. Food portions constraint applied.	The frequency constraints contribute to increasing the consumption of fruits and vegetables in all models, these foods increase by more than 200% compared to the current diet.

			3. Food association constraint applied. 4. Food alternative constraint applied. 5. Constraint on cost.	
114. Barré et al. 2018 France	The second French individual and national study on food consumption (INCA2)	Linear and non-linear programming,	1. Minimization of total absolute departure between the observed and modeled diets, at both the food item and food group level. 2. The total mass of the optimized diet limited to between 80% and 120% of the current intake. 3. The food item, food group and food subgroup amounts constrained to <90th percentile of current intake levels. 4. Constraint on cost	All modelled solutions reduced the amount of meat, however those accounting for bioavailability and coproduction links reduced meat to a lesser extent.
115. Benvenuti et al. 2016 Italy	106 different dishes from Italian primary school	Binary integer linear programming	1. Constraint applied to deal with the composition (first and second course + side dish) of each meal in the 4-week school lunch menu. 2. Constraint on the maximum allowed weekly and monthly repetition of the same dish. 3. Constraint on the maximum allowed weekly repetition of different food categories.	The models achieved reductions of 20-40% in GHGE and 20-35% in WF, while meeting 7 dietary reference values.
116. Broekema et al. 2020 Netherlands	The second National Individual Survey of Food Consumption (INCA2) 2006-2007	Quadratic optimization	1. Minimization of total squared deviation of food items (baseline amount vs. optimized amount). 2. Diets optimized to mimic different dietary (e.g. vegetarian, vegan) patterns.	Dietary shifts needed to meet targets for environmental footprints would require reductions in meat and dairy but increased intakes of fish, shellfish and plant-based foods. The more GHGE were reduced, the less acceptable were diets considered to be.

117. Chaudhari and Krishna 2019 Multi-country	Data on the national level supply of 221 food commodities (g capita–1 day–1) for the year 2011 and 152 countries from the Global Expanded Nutrient Supply (GENuS) database.	Quadratic optimization	1. Minimization of relative deviation from current diets. 2. The optimized amount of a particular food item could not exceed the 95th. percentile of current intakes or be lower than lower than 0.1 times the amount in the current diet. 3. The total mass of the optimized diet was constrained to stay between ±20% of the levels in the current diet. 5. Food items that were not consumed in a country due to cultural, religious or availability reasons were restricted from inclusion in the model. 6. The level of alcohol, spices, and drinks such as tea and coffee were kept constant (i.e. same as current intakes).	Mean relative deviations ranged between 72% to 280% depending on the country to keep diets within nutritionally adequate, planetary boundaries.
118. Darmon et al. 2002 Malawi	3-d weighed food records collected from 3- to 6-y-old rural Malawian children during the food-plenty and food-shortage seasons.	Linear programming	1. Minimization of the deviation in the average percentage of energy contributed by each individual food group from current intake levels, while preferentially choosing the foods eaten most frequently. 2. The percentage of energy provided by food groups was constrained to range between the 25th percentile and the 75th percentile of current intake levels. 3. Portion sizes of individual food items were limited to ≤ the 90th percentile of the current intake. 4. Constrained the total number of portions of main meal dishes for	Realistic nutritionally adequate diets, similar to those currently consumed, were achievable for all modeled diet types, except for those that excluded all foods from the meat, poultry, fish, or egg food group in both seasons or all vegetables in the food plenty season.

			one day and snacks selected for a three-day period to ≤ the 75th percentile of current intake levels per season. 5. The number of one-day portions of cereal-based staples was constrained to ≥ the 25th percentile of current intake levels since these foods were consumed on a daily basis in the observed diet. 6. Constraint on cost.	
119. Darmon et al. 2002 France	Dietary data from individuals, 6 mo to 97 y residing in the district of Val de Marne.	Linear programming	1. Minimization of the sum of the absolute portion-size deviations from mean current diets. 2. Portion size for each food were constrained by an upper limit corresponding to the 75^{th} percentiles of current intakes. 3. The energy-contribution of each major food group was constrained to stay between the 10^{th} and 90^{th} percentiles of baseline values. 4. The energy-contribution of each food subgroup was constrained to stay between the 5^{th} and 95^{th} percentiles of baseline values. 5. Foods consumed by <10% of the population were excluded from the optimized diet. 6. Constraint on cost.	The LP algorithm gives the same importance to all foods when minimizing the departure from the mean current diet. When dietary change is needed, a disproportionate decline in less favorable foods could arise in order to keep consuming more favorable foods.
120. Darmon, Ferguson and Briend 2006 France	Dietary data from women aged above 18 years in a cross-sectional survey conducted in the district of Val de Marne.	Linear programming	1. Minimization of absolute difference between energy provided by a food group in the LP diet vs. the current diet. 2. Portion size for each food were constrained by an upper limit corresponding to the 75^{th}	The diets with the lowest cost demanded greater changes from the current diet, including a reduction in the amount of energy from fresh fruits (~85%) and green vegetables (~70%), and an increase in the energy-share from nuts, dried fruits, roots, legumes, and fruit juices.

			percentiles of current intakes. 3. The energy-contribution of each major food group was constrained to stay between the 5th and 95th percentiles of baseline values. 4. Constraint on cost.	
121. Eini-Zinab 2020 Iran	The households Income and Expenditure Survey (HIES) 2016-2018	Linear programming and goal programming	1. Individual food items constrained to increase by a maximum of 50% and reduce by a maximum of 50%. 2. Cost minimized.	The model minimizing the carbon footprint of the diet increased amounts of cereals, vegetables, fruits, dairy, legumes, nuts, poultry meat and sugar. Combining priorities for cost, carbon and water footprints, and nutrient adequacy in the goal programming model, increased the amount of cereals, vegetables, fruits, dairy and poultry, but reduced the amount of legumes, nuts and sugar as compared to the GHGE-minimizing model.
122. Fakosová et al. 2019 Check Republic	Data from the Czech National Food Consumption Survey 2016.	Linear programming	1. Minimization of total relative deviation from current diets. 6. Constraint on cost.	The optimized FB that was affordable for the lowest-income groups (those with a minimum wage), contained 76 foods and had an average relative deviation of 10%/ food group.
123. Ferguson et al. 2004 Malawi	3-d weighed food records collected from rural 3- to 6-y-old Southern Malawian children.	Linear programming	1. Minimization of the deviation in the average percentage of energy contributed by each individual food group from current intake levels, while preferentially choosing the foods eaten most frequently. 2. The percentage of energy provided by food groups was constrained to range between the 25th percentile and the 75th percentile of current intake levels. 3. 3-day food portions constrained to ≤90th percentile of observed intake levels.	The applied method was deemed suitable for both inform food based dietary guidelines as well as to test their robustness. The modelled solutions for Malawian children prioritized daily intakes of maize flour, dry fish, and leaf relish. There solutions differed somewhat depending on the season.

			4. 1-day portions of main meal dishes and snacks constrained to ≤75th percentile of intake levels and 1-d portion of cereal-based staple constrained to ≥25th percentile of intake levels.	
124. Green et al. 2015 UK	The UK National Diet and Nutrition Survey (NDNS)	Quadratic programming	1. Minimization of total relative deviation from current diets based on expenditure share and price elasticity of different food groups 2. Cost considered.	Above a 40 % reduction in GHG emissions, the average relative deviation of foods was increased dramatically (from 40-50% to up to around 200% with a 60% reduction in GHG).
125. Gurmu et al. 2019 Ethiopia	Food balance sheets	Linear programming	1. Minimization of total relative deviation from current diets. 2. The weight of each food within their specific group was constrained to a maximum level to achieve dietary diversity. 3. Constraint on cost.	The modeled rural food basket that deviated the least from the current diet showed an average relative deviation (ARD) of 3.3% compared with none (0%) in the urban food basket. The modeled food baskets that were nutritionally adequate and that deviated the least from the current diet contained 64 and 79 foods.
126. Henson 1991 UK	UK National Food Survey 1990	Linear programming	1. 52 palatability constraints applied, i.e. the portion-ratios between different food groups were constrained to the normal ratio in which they were consumed. Cost was minimized but not defined as a DA-component.	Applying palatability constraints resulted in a greater flexibility in food consumption patterns since these constraints allowed for a greater variation in consumption.
127. Horgan 2016 UK	UK National Diet and Nutrition Survey (NDNS) 2008-2011.	Linear programming	1. Food amounts were allowed to gradually increase/decrease by 1 to 50 % in steps of 1 %. 2. When no solutions were found for relative changes of 50%, lower limits of -75% or -100% were imposed while keeping the upper limit of +50%.	Few individuals were able to meet both nutrition and environmental targets without exceeding the relative change of their diets more than 50%. Meeting nutritional constraints reduced food related GHGE slightly, but to also achieve GHGE-targets, greater changes to the current diet were required.

128. Johnson-Down et al. 2019 Canada	24-h food recalls from the First Nations Food, Nutrition and Environment Study.	Linear programming	1. Minimizing the sum of the absolute difference between the portion size of a food group in a hypothetical modeled diet and the observed diet. 2. Traditional foods constrained to a minimum of 50% and a maximum of 100% of baseline amounts, except for sweet drinks, coffee whitener, fats, high-sugar foods and processed meats could not exceed baseline amounts. 3. Constraint on cost.	Women and men met all nutrient constraints in models with no DA-constraints, but certain recommended food amounts deviated more than 100% from the current intake levels. Applying DA-constraints affected nutrient adequacy negatively but resulted in food amounts that reflected current intake levels better.
129. Kramer et al. 2017 Netherlands	The Dutch National Food Consumption Survey 2007–2010 (DNFCS)	Linear programming	1. Changes to the current diet were minimized through a penalty score: a weighted sum of serving changes for each product. To capture dietary preferences in the model, the penalty weights were proportional to popularity and directionally dependent. The quantity consumed during the DNFCS were used as a proxy for popularity. The more popular a food, the lower its penalty weight for increased consumption and the higher its penalty weight for decreased consumption.	The higher constraint on environmental impact, the more changes were required compared to current diets. Reductions on environmental impact greater than 21-30% implied unrealistic changes to the diet.
130. Lauk et al. 2020 Estonia	The Estonian National Dietary Survey (ENDS) 2007	Linear programming	1. Minimization of total relative deviation from current diets. 2. Food group constrained to contain a minimum number of different foods. 3. The weight of each food within their specific group was constrained to a maximum level to achieve dietary diversity. 4. Constraint on cost.	Optimized diets only meeting nutrient constraints were affordable to a minimum-wage household. Optimized diets only meeting food based dietary guidelines were not fully nutritionally adequate. Optimized diets meeting nutrient and food based dietary guideline constraints were less affordable and deviated the most from baseline diets.

131. Maillot et al. 2010 France	The National Individual Survey of Food Consumption (INCA) 1998-1999	Linear programming	1. The amount of energy provided by each food groups was constrained to the 5th and the 95th percentile of current intakes. 2. Same as above but additionally extended to the 20 food sub-groups and to the 36 food categories. 3. The total mass of a food was constrained not exceed the 95th percentile limit for that food. 4. Unpopular foods (consumed by < 2.5% of the population) were excluded from the optimized solutions. 5. Foods consumed by less than 5% of the French population were allowed in the optimization model. 6. Constraint on cost.	The progressive imposition of DA constraints increased the diet cost compared to the cost-minimized solutions, without improving nutrient content.
132. Maillot 2010 France	The National Individual Survey of Food Consumption (INCA) 1998-1999	Linear programming	Minimization of the departure from the observed diet for each individual forcing the algorithm to preferentially select foods from each individual's food-repertoire, to only minimize the decrease in repertoire foods, to if necessary introduce new foods popular among other individuals. 2. Total mass of a food, food group and sub food group equal to the 95th percentile of the observed consumption. 3. The total weight of the optimized diet was constrained to not exceed 115% of the observed weight for each individual.	Dietary changes to meet a nutritionally adequate diet differed depending on the individuals baseline diet. In general, plant-based foods, fresh dairy and fatty fish increased in the optimized diets while red meat, solid dairy, salted and sweet snacks decreased.

133. Maillot 2011 France	The National Individual Survey of Food Consumption (INCA) 1998-1999	Linear programming	Minimization of the departure from the observed diet for each individual forcing the algorithm to preferentially select foods from each individual's food-repertoire, to only minimize the decrease in repertoire foods, to if necessary introduce new foods popular among other individuals. 2. Total mass of a food, food group and sub food group equal to the 95th percentile of the observed consumption. 3. The total weight of the optimized diet was constrained to not exceed 115% of the observed weight for each individual.	Dietary changes to meet a nutritionally adequate diet differed depending on the individuals baseline diet In general, the optimized diets mirrored the food group pattern of the Mediterranean diet.
134. Maillot & Drewnowski 2010 USA	2001–2002 National Health and Nutrition Examination Survey (NHANES)	Linear programming	1. Minimization of total relative deviation from current diets 2. Food groups were constrained to keep between the 10th and 90th percentiles of the observed consumption. 3. Food subgroups and food categories were constrained to be lower or equal to the 75th percentile of the observed consumption	Optimized diets to meet nutrient and food group constraints included more fruits and vegetables but had a higher cost than the observed diet. Solid fats and added sugars contributed up to 33% of total energy in the optimized diet, than the MyPyramid diet allows.
135. Maillot et al. 2017 France	The second National Individual Survey of Food Consumption (INCA2) 2006-2007	Linear programming	1. Minimization of total relative deviation from current diets. 2. Constraint on cost.	The dietary changes resulting from the optimization were in general comparable across income-quintiles, yet to fulfil nutrient recommendations, a greater fruit and vegetable intake would be needed for those belonging to the low-income quintile. For those having an observed diet cost <3.85 euros/day, a greater deviation from their current intake would be required in order to have a nutritionally adequate diet, as compared to the rest of the population.

136. Milner et al. 2017 India	The Indian Migration Study (IMS) 2005-2007	Quadratic optimization	1. Minimization of total sum of squared percentage changes of food groups (baseline amount vs. optimized amount). 2. Cost considered.	The optimized diets, meeting constraints for WF, energy content, and nutrient adequacy, contained less GHGE, and implied moderate reductions in amounts of wheat, dairy, and poultry, and moderate increases in amounts of legumes. The dietary changes required for a future 2050 WF-reduction scenario would be more pronounced.
137. Nykänen et al. 2018 Ethiopia	Food balance sheets	Linear programming	1. Minimization of total relative deviation from current diets. 2: Food groups were constrained to a maximum/minimum relative deviation. 3. The weight of each food within its corresponding food group was constrained to a maximum level in different steps. 4. Constraint on cost but not defined as a DA-component.	The progressive imposition of DA constraints increased the diet cost.
138. Parlesak et al. 2016 Denmark	Danish food intake survey 2011–2013	Linear programming	1. The maximum relative deviation of the different food categories constrained to match mean levels in the current diet. 2. Constraint on cost but not defined as a DA-component.	Optimizing for minimum cost while applying nutritional and DA constrains tripled the cost compared to a cost-minimized food basket fulfilling only nutritional constraints.
139. Perignon et al. 2019 Tunisia	National dietary survey performed as part of the Transition and Health Impact in North Africa (TAHINA) project, 2005.	Quadratic optimization	1. Minimization of the squared deviation from the average observed intake for each food item and food group. 2. Energy constrained to match observed energy intake. 3. Total diet weight constrained to deviate by±20% relative to observed levels. 4. The food item, food group and food subgroup amounts constrained to range	Meeting nutrient constraints only increased environmental footprints. Reductions in GHGE of more than 40% impaired the cultural acceptability of the diet. Meeting both nutrient and GHGE constraints reduced levels of red meat but the total amount of animal products mirrored baseline levels.

			between the 5th and 90th percentile of current intake levels.	
140. Rao et al. 2018 India	Indian National Sample Survey (2011–12)	Linear programming	1. Minimization of total deviations (by weight) from present diets. 2. The energy-contribution of each major food group were held constant. 3. Constraining relative deviation of food items within food groups to a maximum increase of 100% and a maximum reduction of 90%. 4. Certain miscellaneous food items were held constant. 5. The share of rice and wheat from Public Distribution System (PDS) and non-PDS were constrained to the same as baseline values. 6. Constraint on cost but not defined as a DA-component.	Households above the poverty line could meet nutritional requirements without exceeding their current food budgets. Minimizing GHGE while meeting nutritional constraints would be affordable to the higher income groups but not the lower income groups. If households aim to achieve nutritional adequacy by minimizing overall deviations, they would have to reduce animal products and consume more of other nutrient dense but cheaper foods, resulting both a reduced cost and reduced emissions.
141. Reynolds 2019 UK	UK Living Cost and Food Survey (2013)	Linear programming	1. The relative change of individual foods was constrained so that they could increase by a maximum of 200%. Individual foods were allowed to be reduced in steps of 1% until no feasible solution was found. 2. Constraint on cost but not defined as a DA-component.	Changes in diets for all income groups were needed to achieve reduced GHGE. Changes in each income group was restricted by the budget of each group, but the highest income group needed to make less changes to their diet compared to the lowest income group, and this was due to the greater food budget in the former group.
142. Ribal et al. 2016 Spain	47 different dishes relevant for the Spanish school meal context	Integer goal programming	1. Constraint applied to deal with the composition (first and second course + side dish) of each meal in the 4-week school lunch menu. 2. Constraint on the maximum allowed weekly and monthly	School meal menus that are affordable and climate friendly were achievable using the proposed optimization model. A lower cost of the optimized diets was not associated with increased climate footprints or an impaired nutrient content.

			repetition of the same dish. 3. Cost considered.	Not all dietary reference values were met in the optimized menu.
143. Scarborough et al. 2016 UK	National Diet and Nutrition Survey (NDNS) 2008-2011	Non-linear programming	1. Minimization of total squared deviation of 125 food categories (baseline amount vs. optimized amount). 2. Cost considered.	Diets optimized to meet the Eatwell Guide contained more starchy carbohydrates but less animal products and less unhealthy sweet/savory snacks. The optimized cost of the diet mirrored the baseline cost.
144. Smith 1959 USA	Michigan state University Consumer Panel 1955	Linear programming	1. Food list contained items that were consumed by a certain proportion (depending on the food group) of families. 2. Constraints on ratios/links between specific foods (e.g. flour and yeast). 3. foods to protect against monotony. 4. Minimized cost.	The more constraints to conform with people’s food preferences, the lower is the possibility to reduce the cost of the diet, although the proposed diet models are still able to reduce the cost of food purchases while ensuring a nutritious diet.
145. Sobhani et al. 2019 Iran	Food frequency questionnaire from a sample of adults in Urmia, Iran.	Linear programming	1. The minimum amount of food items was constrained to ≥ first quartile of the observed intake while the maximum amount of food items was constrained to ≤ first quartile of the observed intake. 3. Energy was equal to observed levels.	The greatest reductions in WF were obtained in Scenario 1 where the modelled diet was designed to meet the energy constraint only. When adding constraints on food groups in Scenario 2, the WF was reduced to a lesser extent. Additionally adding constraints for the diet to meet dietary reference values reduced WF more than Scenario 2, but not as much as Scenario 1.
146. Soden 1992 UK	NA	Linear programming	1. Minimization of the departure from the original quantity of food and modelled diet. 3. Allowing for constraints on the upper and lower limit of food quantities. 2. Allowing for ratios between selected food items to be linked when setting up food-constraints.	NA

147. Song et al. 2017 China	The China Health and Nutrition Survey (CHNS) 2004, 2006, 2009, 2011	Uncertainty Linear Programming	1. Food groups constrained to reduce by a maximum of 50% compared to observed levels. 2. The maximum increase of food groups was set to the 99th percentile of current intakes.	GHGE-minimized diets reduced footprints by almost 50% but lacked diversity and were deemed unrealistic. Adding acceptability constraints limited abilities to reduce GHGE (reduced by 7-28%). Red meat was reduced in general, although poultry meat was increased in the optimal diet scenarios.
148. Tyszler, Kramer and Blonk 2016 Netherlands	The Dutch Consumption Panel (2011)	Linear programming	1. Changes to the current diet were minimized through a penalty score. Changes to the current diet were translated into a penalty score: a weighted sum of serving changes for each product. To capture dietary preferences in the model, the penalty weights were proportional to popularity and directionally dependent. The quantity consumed during the DNFCS were used as a proxy for popularity. The more popular a food, the lower its penalty weight for increased consumption and the higher its penalty weight for decreased consumption.	Eating healthier is not necessarily beneficial for the environment. Diet related GHGE can be reduced by 30% while ensuring nutritional adequacy and with relatively low deviations from the current Dutch diet.
149. van Dooren 2015 Netherlands	Dutch National Food Consumption Survey 2007–2010.	Linear programming	1. Minimization of the absolute changes in terms of portions to the current diet weighted by a proxy of popularity (popular product getting a lower penalty score while a non-popular food got a higher score). 2. Constraint on cost but not defined as a DA-component.	It was possible to reduce food related GHGE by 50% while fulfilling dietary guidelines and keeping close to current diets.

150. van Dooren and Aking 2016 Netherlands	Dutch National Food Consumption Survey 2007–2010.	Linear programming	1. Minimization of the absolute changes in terms of portions to the current diet weighted by a proxy of popularity (popular product getting a lower penalty score while a non-popular food got a higher score).	The optimization resulted in a nutritionally adequate diet with a low climate impact and a low land use. An optimal diet for the Low Lands was achievable that was nutritionally adequate and more sustainable than diets such as the Mediterranean diet, the New Nordic diet or a traditional Low Lands diet.
151. Verly-Jr et al. 2019 Brazil	National Dietary Survey (NDS) and Household Budget Survey (HBS) 2008/2009.	Linear programming	1. Minimization of the relative difference between baseline and optimized food quantities. 2. A lower limit for each food was set to the 10th percentile of current intakes in each population strata, while three different upper limits were used representing the 70th, 80th and 90th percentiles of current intakes. 3. Constraint on cost but not defined as a DA-component.	More nutritious and affordable diets could be achieved with minor changes to current diets (changes only affecting some foods). With no constraint on cost, it was however sill hard to reach nutritional adequacy due to the DA constraints.
152. Vieux et al. 2018 France UK Italy Finland Sweden	National FINDIET 2012 Survey in Finland. Riksmaten 2010 study in Sweden. INRAN-SDAI-2005 study in Italy. NDNS rolling program for 2008–2012 in the UK. INCA2 study 2006–2007 in France	Linear programming	1. Minimization of total relative departure between the observed and modeled diets, at food item level. 2. The total mass of the optimized diet was constrained to stay between ±20% of the levels in the current diet. 3. Diet weight per food item and food sub-food group were constrained to between the 10th and the 90th percentile of the observed intake. 4. Ratio of solid-to-liquid food weights, maximal amounts of alcoholic beverages, fish oil and offal, and total energy intakes were constrained to the observed intake.	Achieving nutritional adequacy was not always associated with a reduced climate impact. The more reductions in GHGE, the greater changes to the diet were needed.

153. Wilde and Llobrera 2009 USA	2001–2002 National Health and Nutrition Examination Survey (NHANES)	Quadratic programming	1. Minimization of total relative departure between the observed and modeled diets, at food item level. 2. Food category constraints according to the *MyPyramide*. 3. Constraint on cost.	The optimized diet deviated substantially from the current consumption when constraints on *MyPyramid* food categories were met. Complying with the Thrifty Food Plan cost target resulted in high deviations from current diets.
154. Wilson et al. 2013 New Zealand	National survey data from the New Zealand Adult Nutrition Survey Wellington	Linear programming	1. DA was approached by allowing optimized solutions to include “more familiar meals”. 2. Cost was minimized.	The diets with DA constraints tended to have a higher cost and GHGE than the diets only having nutritional constraints (while minimizing cost).