Dietary quality, greenhouse gas emissions related to food consumption, and human health:

A population-based cohort study in northern Sweden

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ABSTRACT

The overall aim of this thesis was to assess dietary quality and dietary-related greenhouse gas emissions (GHGEs), and their association with health outcomes, in a population-based cohort in northern Sweden.

Dietary data were collected among participants within the cohort Västerbotten Intervention Programme by a food frequency questionnaire between 1990–2016. Dietary GHGEs were estimated using the RISE Food and Climate Database. Dietary nutrient density was calculated by the Nutrient Rich Foods (NRF) index in Study I and Study II. In Study I, fifteen variants of the NRF index were evaluated and the index version that best predicted all-cause mortality was further used to estimate participants' nutrient density in Study I and Study II. In Study III, diet quality was assessed by the Swedish Healthy Eating Index for Adults 2015 (SHEIA15), based on the 2015 Swedish food-based dietary guidelines. Cox proportional hazard regressions were performed to investigate associations between dietary aspects and health outcomes.

Study I investigated associations between the NRF index and all-cause mortality, as well as associations between diets with varying levels of nutrient density and GHGEs, and all-cause mortality. The NRF11.3 index was indicated as a predictor of mortality hazard. The study also showed that diets with higher nutrient density and lower GHGEs were associated with lower mortality hazards in women, and that diets with lower nutrient density and lower GHGEs were associated with higher mortality hazards in men.

Study II investigated associations between diets with different levels of nutrient density and GHGEs, and myocardial infarction (MI), and stroke. The NRF11.3 index was not indicated as a predictor of MI or stroke. A negative association was however shown between diets with lower GHGEs and MI hazard in men.

Study III investigated the association between SHEIA15, and both all-cause mortality and dietary GHGEs. Lower all-cause mortality hazards and lower dietary GHGEs were indicated with higher SHEIA15 scores.

This thesis demonstrated both potential co-benefits and trade-offs between dietary quality, GHGEs of self-reported diets, and health outcomes in a Swedish population. Furthermore, two indices assessing different aspects of dietary quality of Swedish diets were suggested as predictors of all-cause mortality, of which one was further suggested as a predictor of dietary GHGEs.

Keywords: diet quality, nutrient density, greenhouse gas emissions, climate impact, health, sustainable diet, sustainable nutrition

SAMMANFATTNING PÅ SVENSKA

Vad vi äter har en stor påverkan på både hälsa och miljö. Dåliga kostvanor är en av de främsta riskfaktorerna för hjärt-kärlsjukdomar i både Sverige och globalt, och det globala livsmedelssystemet är ensamt ansvarigt för cirka en tredjedel av de totala utsläppen av växthusgaser, liksom annan miljöpåverkan. Hälsosamma koster från miljömässigt hållbara livsmedelssystem är inte omöjliga att uppnå, men detta kräver förändringar i både livsmedels-produktion och konsumtion. För att kunna undersöka hållbarhet kopplat till livsmedel och koster krävs ett helhetsperspektiv, vilket i sin tur kräver validerade mätmetoder och indikatorer som möjliggör en sammantagen bedömning av kostens påverkan på näringsintag, hälsa, och miljö.

Det övergripande syftet med denna licentiatuppsats och dess tre studier var därför att bidra med kunskap om sambanden mellan kostkvalitet, kost-relaterade växthusgasutsläpp, och hälsoutfall i den populationsbaserade kohorten Västerbotten Intervention Programme (VIP) i norra Sverige.

Studie I undersökte olika aspekter av att konstruera ett index för att mäta näringstäthet. Även sambanden mellan näringstäthet, kostrelaterade växthus-gasutsläpp, och dödlighet undersöktes. Studien indikerade att näringstäthets-indexet NRF11.3 är en prediktor för lägre dödlighet. Studien indikerade vidare att koster med högre näringstäthet och lägre växthusgasutsläpp är associerade med lägre dödlighet hos kvinnor och att koster med lägre näringstäthet och lägre växthusgasutsläpp är associerade med högre dödlighet hos män.

Studie II undersökte vidare sambanden mellan näringstäthet, kostrelaterade växthusgasutsläpp, och hjärtinfarkt samt stroke. Studien kunde inte visa på att indexet NRF11.3 var en prediktor för hjärtinfarkt eller stroke. Däremot indikerade studien ett negativt samband mellan koster med lägre växthus-gasutsläpp och hjärtinfarkt hos män.

Studie III undersökte sambanden mellan ett kostkvalitetsindex och kost-relaterade växthusgasutsläpp, samt dödlighet. Indexet SHEIA15, baserat på de svenska livsmedelsbaserade kostråden från 2015, indikerades som en prediktor för både lägre kostrelaterade växthusgasutsläpp och lägre dödlighet.

Eftersom licentiatuppsatsen är baserad på observationsstudier så kan inga slutsatser dras om orsakssamband för de observerade sambanden mellan kost och hälsa. Sammanfattningsvis indikerade licentiatuppsatsen dock både möjliga synergier och målkonflikter mellan kostkvalitet, kostrelaterade växthusgasutsläpp, och hälsoutfall i en svensk population.

LIST OF PAPERS

This licentiate thesis is based on the following studies, referred to in the text by their Roman numerals.

I. **Strid A**, Johansson I, Bianchi M, Sonesson U, Hallström E, Lindahl B, Winkvist A. Diets benefiting health and climate relate to longevity in northern Sweden. *Am J Clin Nutr*. 2021 Aug 2;114(2):515-529.

II. **Strid A**, Johansson I, Lindahl B, Hallström E, Winkvist A. Towards a more climate-sustainable diet: possible deleterious impacts on health when diet quality is ignored. *Accepted for publication in The Journal of Nutrition.*

III. **Strid A**, Hallström E, Lindroos AK, Lindahl B, Johansson I, Winkvist A. Adherence to the Swedish dietary guidelines and the impact on mortality and climate in a population-based cohort study. *Manuscript.*

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CONTENT

ABBREVIATIONS

BMI	Body mass index
CO_2e	Carbon dioxide equivalents
CVDs	Cardiovascular diseases
FAO	Food and Agriculture Organization of the United Nations
FBDGs	Food-based dietary guidelines
FFQ	Food frequency questionnaire
GBD	Global Burden of Disease
HEI	Healthy Eating Index
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life-cycle assessments
MI	Myocardial infarction
NCDs	Non-communicable diseases
NNR 2012	Nordic Nutrition Recommendations 2012
NRF index	Nutrient Rich Foods index
RISE	Research Institutes of Sweden
SDGS	Swedish Dietary Guidelines Score
SFA	Swedish Food Agency
SHEIA15	Swedish Healthy Eating Index for Adults 2015
VIP	Västerbotten Intervention Programme

DEFINITIONS IN SHORT

Definitions specific for this thesis

Dietary quality	The collective name for dietary nutrient density and diet quality.
Dietary nutrient density	The levels of nutrients to encourage per dietary intake versus the levels of nutrients to limit per dietary intake in comparison with dietary recommendations.
Diet quality	The consumption of foods and nutrients to encourage versus the consumption of foods and nutrients to limit in comparison with dietary recommendations.
Dietary greenhouse gas emissions	The greenhouse gas emissions produced by production and processing of the foods consumed.

General definitions

Co-benefits	The positive effects that one measure might have on other measures, thus increasing the total benefits (1).
Trade-offs	The negative effects on one measure, when positive effects are gained in other measures (2).
Hazard Ratio (HR)	An estimate of the ratio of the hazard rate in the investigated group versus the hazard rate in the reference group. The hazard rate is a theoretical measure of the probability of occurrence of an event per unit time at risk, given that it has not yet happened up until that time (3).

1 INTRODUCTION

Individual dietary choices can be influenced by many aspects, such as health, sociocultural, religious, economical, availability, nutritional, environmental, and emotional aspects, as well as by hunger and appetite. Further, food is undeniably necessary for our survival. However, apart from and beyond the individual values of food, our dietary patterns and the food system have impacts on a global scale. Diet connects two of the main global challenges of our time, namely public health and environmental sustainability (4, 5). Substantial changes in both food production and consumption are required to safeguard diets that are both healthy and environmentally sustainable (4).

Sustainable development was in 1987 defined as “development that meets the needs of the present, without compromising the ability of future generations to meet their own needs” (6). To support sustainable development, sustainable diets have been holistically defined by the Food and Agriculture Organization of the UN (FAO) as “those diets with low environmental impacts that contribute to food and nutritional security and to healthy lives for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, are nutritionally adequate, safe, and healthy, and optimize natural and human resources” (7). Nutrition, health, and environment are thus central aspects of sustainable diets.

Already in 1986, Gussow and Clancy recognized the opportunity to include environmental aspects in dietary guidelines in addition to nutritional and health aspects (8). This was followed up in 2019, when the FAO and the World Health Organization published guiding principles aiming to aid countries transform food systems to deliver sustainable healthy diets (5). In the same year, the EAT-*Lancet* Commission published global scientific targets for healthy diets and sustainable food production, to aid the achievements of the UN Sustainable Development Goals and the Paris Agreement (4). The EAT-*Lancet* Commission proposed substantial dietary shifts and suggested a healthy reference diet consisting of a variety of plant-based foods, low amounts of animal-based foods, unsaturated compared to saturated fats, and small amounts of refined grains, highly processed foods, and added sugar (4).

However, diets with lower environmental impacts do not necessarily equal nutritious and healthy diets (9-11), and vice versa (12). Increased intakes of plant-based foods and restricted intakes of animal-based and discretionary foods, as well as not eating more than needed to maintain a healthy body weight, are habits often promoted in the quest for more sustainable dietary habits in affluent countries like Sweden (4, 13-15). However, within broader food groups, there is a spread in environmental impact and nutritional quality of specific food products (16-18).

Hence, a deeper understanding of the combined environmental, nutritional, and health effects of diets is urgently needed. Nevertheless, further research needs to be executed in development, evaluation and validation of methods and indicators used to integrate interdisciplinary sustainability perspectives of foods and diets to achieve this deeper understanding.

Research questions answered in this thesis are the following:

- Is a nutrient density index a useful predictor of dietary-related health effects in a Swedish population?

- What potential co-benefits and trade-offs exist between dietary quality, dietary greenhouse gas emissions (GHGEs), and health, in a Swedish population?

- Is a diet quality index assessing adherence to Swedish dietary guidelines a useful predictor of all-cause mortality and dietary GHGEs in a Swedish population?

2 BACKGROUND

2.1 DIET AND PUBLIC HEALTH

Dietary related health impacts

In 2017, the health effects of dietary risk factors were systematically evaluated in 195 countries, as part of one of the most thorough observational epidemiological studies published, the Global Burden of Disease (GBD) study (19). The GBD study concluded that in 2017, 11 million deaths and 255 million disability-adjusted life-years were attributable to dietary risk factors, and could have been prevented with improved dietary habits (19). The 15 dietary risk factors investigated were related to both low and high dietary intakes. The ten dietary risk factors related to low dietary intakes were low intake of fruit, vegetables, legumes, wholegrains, nuts and seeds, milk, fibre, calcium, seafood omega-3 fatty acids, and polyunsaturated fatty acids. The five dietary risk factors related to high dietary intake were high intake of red meat, processed meat, sugar-sweetened beverages, trans-fatty acids, and sodium. High intake of sodium, low intake of wholegrains and low intake of fruit were indicated to be the three leading dietary risk factors for deaths and disability-adjusted life-years related to non-communicable diseases (NCDs) in the 2017 GBD study (19). Further, in a later GBD study including data up to 2019, suboptimal dietary habits, measured as joint effects of the previously evaluated 15 dietary risk factors, were indicated as one of the leading preventable risk factors for deaths and disability-adjusted life-years related to NCDs in the world (20).

Based on GBD data, in 2021, the Swedish Institute for Health Care Economics estimated the proportion of cardiovascular diseases (CVDs) that can be attributed to lifestyle factors in Sweden (21). The results showed that over 50% of the cases of ischaemic heart disease, and over 30% of the cases of stroke, could be related to lifestyle factors among both women and men. The main lifestyle risk factor indicated for both ischaemic heart disease and stroke was unhealthy dietary habits, and especially high intakes of sodium, low intakes of wholegrains, and low intakes of vegetables and fruit (21).

Dietary-related risk factors are hence indicated as one of the leading risk factors for NCDs, and especially CVDs, in Sweden (21), and globally (19, 20). Nevertheless, the most recent national dietary survey among adults in Sweden, performed 2010–2011, demonstrated large discrepancies between reported dietary intakes and recommended intakes according to the Swedish national food-based dietary guidelines (FBDGs) (22). For example, the average intake levels in the Swedish population were indicated to be lower than recommended for wholegrains, fruit and vegetables among both women and men, and higher than recommended for red and processed meat among men (22).

Food-based dietary guidelines

National FBDGs have been developed by over 100 countries in the world to aid the promotion of overall health and the prevention of dietary-related NCDs in their populations (23). FBDGs are developed based on existing scientific evidence with an adaptation to the nutritional status, food availability, food culture, and dietary habits of the individual country (23).

The current Swedish FBDGs from 2015 are primarily based on the latest Nordic Nutrition Recommendations (NNR) from 2012 (13, 24). The NNR 2012 are in turn based on an overall assessment of the at the time most current scientific knowledge of the associations between dietary habits, food intakes, nutrient intakes, and health outcomes (24). Compared to previous editions, NNR 2012 emphasizes the role of dietary patterns and food groups compared to single nutrients, to consider the interactions of nutrients and other components in foods and diets. Emphasis is also put on energy balance and physical activity as elements of a healthy lifestyle (24). The emphasis on food groups, energy balance and physical activity is also found in the 2015 Swedish FBDGs named “Find your way to eat greener, not too much and be active” (13). A new NNR is on its way, scheduled for 2023, and thus the Swedish FBDGs will be correspondingly updated.

In the latest Swedish FBDGs both health and environmental sustainability aspects were integrated (13). In addition to being based on the NNR 2012 and knowledge of the population’s dietary habits, the 2015 Swedish FBDGs are thus also based on at the time most current scientific knowledge regarding the environmental impact of various food groups (25). The 2015 Swedish FBDGs include guidelines on increased intakes of vegetables and legumes, fruit and berries, seafood, nuts and seeds, decreased intakes of red and processed meat, salt, sugar, and alcohol, as well as a switch to healthy fats, wholegrains, and low-fat dairy products (13).

Indices of diet quality and nutrient density

Indices of dietary quality can be used to enable evaluations of adherence to FBDGs in populations and sub-populations, and to assess general quality of diets.

The first review investigating indices of overall dietary quality was published in 1996 by Kant, and indices examined were based on nutrients, or on foods/food groups, or on both (26). Already at that time, Kant acknowledged the usefulness of indices that include several dietary aspects concurrently, compared with only assessing individual nutrients, foods or food groups (26). Since then, a vast quantity of dietary quality indices has been developed and published.

One of the first indices to assess adherence to dietary guidelines, and probably one of the most acknowledged, is the Healthy Eating Index (HEI) based on American dietary guidelines by Kennedy *et al* in 1995 (27, 28), which has been further developed and continuously employed since. In Sweden three indices have been published based on Swedish dietary guidelines: a Diet Quality Index based on the Swedish Nutrition Recommendations from 2005 (DQI-SNR) published in 2011 (29); the Swedish Healthy Eating Index for Adolescents 2015 (SHEIA15) published in 2020 based on the 2015 Swedish FBDGs (30); and the Swedish Dietary Guidelines Score (SDGS) published in 2022 updating the DQI-SNR based on the 2015 Swedish FBDGs (31). These indices differ in both number of dietary components and which dietary components that are included, as well as in scoring method.

Nutrient-based indices are another type of dietary quality indices solely including nutrients (32, 33). Previously published indices have been developed for different purposes, such as e.g., monitoring the impact of policy changes or evaluating diet-health relationships (32). Nutrient-based indices have also been developed and used on a food-level, referred to as nutrient profiling, which can be used to guide consumers to healthier food options via front-of-pack labels (33, 34). A new area of application for nutrient-based indices is in life-cycle assessment (LCA), to relate the environmental impact of foods and diets to their nutrient content (35). Commonly, the indices compare nutrient intakes or content to nutrient recommendations (32, 33). However, the construction of the indices differs in several other aspects, such as e.g., nutrients included, scoring system, and if capping or weighting is used or not (32, 33).

The construction of dietary quality indices depends on subjective choices made by the investigator (26, 36, 37), which may impact results (33, 38, 39). Hence, validation of dietary quality indices should be performed, and results need to be carefully interpreted (33, 37, 38).

2.2 FOOD AND ENVIRONMENTAL SUSTAINABILITY

Dietary related environmental impacts

The production and processing of foods lead to immense environmental impacts. The Intergovernmental Panel on Climate Change (IPCC) reported in 2019 that the global food system is accountable for 21–37% of total anthropogenic global GHGEs, contributing to climate change, which in turn impact food and water security and ecosystems, and contribute to regional desertification and land degradation (40). A review by Poore and Nemecek from 2018 further report that approximately 32% of global acidification and 78% of eutrophication can be linked to food production, possibly leading to fundamental changes of ecosystems, impacting biodiversity and ecological resilience (17). Global agriculture is further resource intensive, using 43% of the global land mass that is habitable (land free of desert and ice) and 70% of global freshwater resources (17, 40).

Due to population and income growth, increases in GHGEs from food systems are expected (40). Nevertheless, environmental impacts have been shown to vary substantially among producers of the same food product, indicating the potential of improving productivity and decreasing environmental impacts of food production (17). Large variations in environmental impact among food products are also reported, especially between plant-based foods and animal-based foods, indicating the potential for environmental impact reduction of changes in food consumption patterns (17, 18). In a study from 2021 of the total dietary GHGEs of a Swedish population, results showed that reported intakes of animal-based food products were responsible for 71% of dietary GHGEs and that intake of discretionary foods were responsible for 12% of dietary GHGEs (18). This highlights not only the GHGE reduction potential of a consumption switch from animal-based foods to more plant-based foods, but also the impact of limiting foods low in micronutrients. The Swedish study further indicated that food loss and waste was responsible for 18% of dietary GHGEs (18), further indicating an opportunity of reducing dietary GHGEs.

Hence, changes in food production and food consumption patterns are possible and imperative to ensure environmentally sustainable food systems.

Life-cycle assessment

A commonly used and standardized tool for studying the environmental impacts of food products is LCA (41). LCA enables a quantitative assessment of the potential environmental impacts of all the stages over the entire life cycle of a food product, “from cradle to grave” (42). An LCA study is made up of four phases according to the International Organization for Standardization (ISO) 14040 series standard: goal and scope definition (formulating the goal and defining the boundaries, functional unit and impact categories of the study); inventory analysis (collecting data, quantifying inputs and outputs); impact assessment (quantifying the magnitude of environmental impacts): and interpretation (evaluating completeness and quality of results; assessing uncertainties; interpreting results in relation to the defined goal and scope to reach conclusions and recommendations) (41, 43).

A basic element in LCA studies is the functional unit, which is a quantitative description of the function of the product investigated and the reference unit to which all environmental effects are related (41). For food products the most commonly employed functional unit is that based on mass of the product, e.g., by presenting the environmental impact per kg of food produced (41). Nevertheless, over the last years increasing attention has been paid towards including nutritional aspects as complementary functional units of food, to better reflect important functions of food (35, 41).

Even though LCA is a standardized and often recommended method for studying environmental impacts of food products, methodological issues exist (41). Cucurachi *et al* highlights that previous LCA research has primarily focused on a limited selection of foods and environmental impact categories, such as climate impact, and suffers from geographical bias, potentially leading to underestimation of the environmental impacts of the global food system (41). Other uncertainties raised regarding LCA studies impacting results and important to keep in mind include uncertain input data and different method choices, e.g., impact assessment method, functional unit, system boundaries, and allocation method (e.g., how to allocate environmental burdens between co-products from the same production system) (42, 44).

2.3 NUTRITIONAL EPIDEMIOLOGY

Nutritional epidemiology, a subdiscipline to epidemiology, is a research field that investigates the relationships between dietary factors and disease occurrence (45). Since dietary intake is an exposure that is complex and challenging to assess, diet-disease relationships are difficult to determine (46).

Study design

To study the relationships between dietary factors and disease occurrence, several study designs exist, both observational and experimental. Two major study designs in observational nutritional epidemiology are the cohort study design and the case-control study design. Nevertheless, the study design that generates the strongest evidence for associations is the experimental study design (46).

Prospective cohort studies entail assessments of dietary intake of disease-free subjects, who are then followed over time to assess health outcomes (45, 46). By only including disease-free subjects in the beginning of the study, the temporal dimension is ascertained, i.e., that the dietary exposure is seen to occur before the health outcome (47). However, it is a costly and time-consuming study design (47).

Case-control studies entail that the dietary intake data of subjects with and without a disease, i.e., cases and controls, are assessed and compared (46). Case-control studies are usually more efficient, fast, and cheap than cohort studies, since the number of subjects is generally smaller and there is no follow-up (45, 48). However, the chronology of dietary exposure and disease cannot be ascertained in this study design unless exposure data have been collected previously for example within an existing cohort, and this is a limitation of case-control studies (46, 48).

For both cohort studies and case-control studies, confounding factors can be controlled for either in the design, by matching subjects, or in the statistical analysis, by using multivariable models (45). Nevertheless, adjusting for potential confounders in the statistical analysis requires that information on confounding factors have been collected (45).

Dietary assessment methods

Both cohort studies and case-control-studies require dietary intake data to investigate the relationship between dietary factors and disease occurrence (46). To assess dietary intakes, there are several different dietary assessment methods available, each with their own advantages and limitations (46).

The retrospective food frequency questionnaire (FFQ) is the most commonly used dietary assessment method in large epidemiologic studies since it is low-cost, the report burden is considered small, and it captures habitual diet in a self-administered manner (45, 46). FFQs entail that study subjects indicate their usual consumption frequency of a food product or food group, and this dietary information can be used to rank the subjects by dietary intake (45, 46). Since the FFQ is a retrospective method, it relies on the memory of the study subject, and recall bias is thus possible (46). Repeated FFQ assessments could possibly improve the estimations of dietary intakes compared to single FFQs, since possible dietary changes are captured (46).

The retrospective 24-hour recall and food diaries are other commonly used dietary assessment methods. They assess current diet but are able to assess usual diet by being repeated (46). A 24-hour recall entail that the study subject is interviewed regarding the dietary intakes of the previous 24 hours (46). The food diary is instead self-administered, and the study subject is meant to record the dietary intakes at the time of consumption (46). The 24-hour recall rely on the ability of the study subject to recall the dietary intake, and for the food diary actual intakes can be affected by the food recording itself, introducing bias (46).

Misreporting is an inherent problem for all dietary assessment methods and is hence a key challenge within the research field of nutritional epidemiology (46). Underreporting of energy intake has been indicated to be related to personal characteristics such as body mass index, and it has further also been indicated as selective with regards to dietary intakes of fat and sugar, introducing bias (46, 49, 50). To partly handle misreporting of energy intake, energy adjustment is recommended (46).

Further, self-reported dietary data generally suffer from both random and systematic errors, impacting results in different ways (46, 51). Habitual diet is generally difficult to capture due to large day-to-day variation, leading to random errors in the assessment of dietary intake (46). Random errors could lead to attenuation of estimated associations between dietary intakes and health outcome (46). Systematic errors could instead lead to inaccurate conclusions about estimated associations between dietary intakes and health outcomes (46). Information bias, i.e., systematic errors in measurements of dietary intake or other covariates, and selection bias, i.e., systematic errors when including study subjects, are examples of systematic errors (46). Both random and systematic errors could be due to several different factors, however, all possible errors need to be considered in the interpretation of diet-disease associations to ensure that accurate conclusions are made.

3 AIMS

The overall aim of this thesis was to assess dietary quality, greenhouse gas emissions (GHGEs) of food consumption, and the association with health outcomes, in a population-based cohort in northern Sweden. The specific aims were:

- To evaluate a nutrient density index, the Nutrient Rich Foods (NRF) index, and associated methodological choices, against all-cause mortality (Study I)
- To examine the association between the NRF index, and myocardial infarction (MI) and stroke morbidity (Study II)
- To evaluate the association between diets with different levels of GHGEs, and myocardial infarction and stroke morbidity (Study II)
- To examine the association between diets with different levels of nutrient density and GHGEs, and all-cause mortality as well as MI and stroke morbidity (Study I & Study II)
- To assess the association between a diet quality index, the Swedish Healthy Eating Index for Adults 2015 (SHEIA15), and all-cause mortality (Study III)
- To assess the association between SHEIA15 and GHGEs from diets (Study III)

4 SUBJECTS AND METHODS

The three studies in this thesis were all based on health and lifestyle data from the population-based prospective cohort study Västerbotten Intervention Programme (VIP), placed in Västerbotten in northern Sweden (52). An overview of the aims, study design, subjects, and data collection of the three studies included in the thesis can be found in *Table 1*.

Table 1. Overview of the three studies included in the thesis

Study	Aims	Study design	Study subjects	Data collection
I	Evaluate the NRF index against all-cause mortality. Examine the association between dietary nutrient density and dietary GHGEs, and all-cause mortality.	Population-based cohort study.	In total, 49,124 women and 47,651 men, aged 35–65 years, from VIP.	Food intake and lifestyle data from a questionnaire including a 84- and 64-question semiquantitative FFQ from VIP. GHGE data for food products from the RISE Food Climate Database. Energy and nutrient content data for food products from the national food composition database at the SFA. Data on diagnoses and deaths from “Patient” and ”Cause of death” registers at the National Board of Health and Welfare in Sweden.
II	Examine the association between the NRF index, and MI and stroke. Examine the association between dietary GHGEs, and MI and stroke. Examine the association between dietary nutrient density and dietary GHGEs, and MI and stroke.		In total, 41,194 women and 39,141 men, aged 35–65 years, from VIP.	
III	Assess the association between SHEIA15 and all-cause mortality. Assess the association between SHEIA15 and dietary GHGEs.		In total, 49,124 women and 47,651 men, aged 35–65 years, from VIP.	

Abbreviations: FFQ, Food frequency questionnaire; GHGEs, greenhouse gas emissions; MI, myocardial infarction; NRF index, Nutrient Rich Foods index; RISE, Research Institutes of Sweden; SFA, Swedish Food Agency; SHEIA15, Swedish Healthy Eating Index for Adults 2015; VIP, Västerbotten Intervention Programme.

4.1 THE VÄSTERBOTTEN INTERVENTION PROGRAMME

VIP was launched in 1985 and continually collects health and lifestyle data based on both a physical health screening and a health and lifestyle questionnaire, completed at the study subjects' local health care centers (52). The health and lifestyle questionnaire was harmonized among the Västerbotten communities and became electronically readable in 1990. The data collected at the physical health screening includes height, weight, blood pressure, data from an oral glucose tolerance test, and data on blood lipids. The health and lifestyle questionnaire includes questions on socioeconomic conditions, health, social support and network, work stress, physical activity, tobacco consumption, alcohol consumption, sleeping habits, eating habits, and a FFQ (52).

As a response to increasing CVD mortality in Sweden and an especially high CVD mortality in the county of Västerbotten in the mid-1980s, VIP was launched as a community intervention programme with the aim to reduce CVD and diabetes morbidity and mortality (52). VIP has a population-based approach and a strategy to reach all middle-aged inhabitants, and hence yearly invites Västerbotten inhabitants turning 40, 50 and 60 years of age to their local health care center (52). During a few years in the beginning of the study, inhabitants turning 30 years of age were also invited, but because of low attendance rates and budgetary restrictions they were omitted in the mid-1990s. The participation rate has increased over time, from 48–57% during 1991–1995 to 66–67% since 2005 (52). In 1998, a study of social selection bias in social and health factors in VIP during the years 1992 and 1993 was performed, indicating that differences in social characteristics between VIP participants and non-participants were marginal (53).

For the included study subjects, baseline data were collected between 1990–2016 (*Figure 1*).

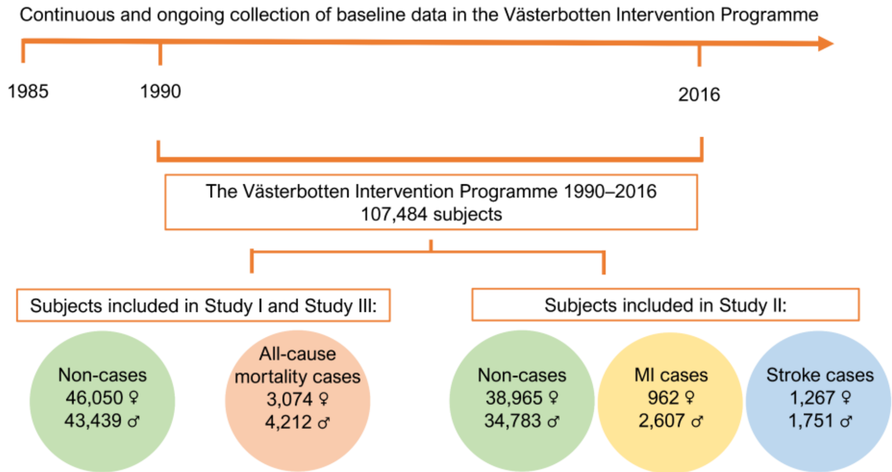

Figure 1. Flowchart of inclusion of study subjects from the Västerbotten Intervention Programme into the three studies included in the thesis.

Exclusion criteria for all the three studies in the thesis encompassed if at baseline the study subjects' age was below 35 years or over 65 years, their height was below 130 cm or over 210 cm, their body weight below 35 kg, or their body mass index (BMI) below 15.0 or missing. If the food intake level was below the 1st percentile or above the 99th percentile, and if over 10% of the food intake data was missing, and/or data was missing on portion size, study subjects were also excluded. For Study II, further exclusion criteria included an energy intake below the 1st percentile or above 5000 kcal (54). The rationale for these exclusion criteria was to clear the dataset from implausible data with regards to energy intake, height, and body weight. This list of exclusion criteria has been prepared by the researchers responsible for the VIP dataset and is applied by all data users, so that data analyses of VIP are uniform. We further excluded participants <35 years and >65 years since these age groups are very small due to the primary invitation goal of VIP to yearly invite citizens turning 40, 50 and 60 years of age, but also to further adjust for age as a confounder. Further, the dataset used for Study II was originally prepared for a study investigating the association between intake of dairy products and cardiometabolic diseases by Johansson *et al* (54). Therefore, participants who emigrated or immigrated during the follow-up period were excluded since they were assumed to be mostly of non-Swedish heritage and hence to have a higher prevalence of lactose-intolerance (54).

Dietary assessment method

The dietary assessment method used to collect data on food intake in VIP was a retrospective semiquantitative FFQ (52). Two versions of the FFQ were used during the time period when baseline data were collected for the included study subjects (1990–2016). The two FFQ versions had different lengths (84 questions or 64 questions) but were largely including the same food products and food groups. All questions were referring to the intake of the previous 12 months and could be answered with nine frequencies. Average portion sizes were aided by four illustrations of plates indicating increasing amounts of meat, potato, and vegetables, as well as by age- and gender standardized portion values (55). The food intake data from the longer version with 84 questions (used 1990–1996) was harmonized to match the food intake data from the condensed version with 64 questions (used since 1996).

The 84-question version of the VIP FFQ has been validated against ten repeated 24-hour diet recalls in a randomly selected representative subsample of 195 participants (55). The validation study from 2002 indicated that the FFQ intake estimates of fish, meat, alcoholic beverages, and sweets were lower, and that of vegetables, fruit, bread, cereals, rice, potatoes, pasta, and dairy products, were higher than the intake estimates of the 24-h recalls (55). Estimated intakes of energy and nutrients were indicated as similar between the FFQ and the 24-hour recalls, except for vitamin C, dietary fibre, beta-carotene, and retinol (lower in FFQ), and cholesterol and sucrose (higher in FFQ). Still, it was concluded by Johansson *et al* that the FFQ intake estimates have good reproducibility and are on a level of validity similar to other prospective cohort studies using FFQs as the dietary assessment method (55).

With the help of the average and standard portion sizes, the reported intake frequencies of all food products and food groups were converted into quantities of grams per day. Energy and nutrient intakes per day were also estimated by multiplying the portion size value with energy and nutrient content information from the national food composition database from the SFA, using the software MATs (Rudans Lättdata, Sweden) (55). Since data on added sugar was missing in the national food composition database, intake of added sugar was estimated from unpublished data on added sugar content from the SFA (56).

All estimated nutrient intakes and food intakes were further adjusted for energy intake and standardized to 2000 kcal per day for women and 2500 kcal per day for men. This was done to enable an assessment of diet quality instead of an assessment of diet quantity (36), as well as to partly adjust for expected underreporting of dietary intake (46, 57).

4.2 THE NUTRIENT RICH FOODS INDEX

The nutrient density index, the NRF index, was used to evaluate the study subjects' dietary nutrient density in Study I and Study II of this thesis.

The NRF index was originally developed by Drewnowski *et al* to enable a composite evaluation of the nutrient density of individual food products (58, 59). In the US in 2009, methodological aspects of the NRF index, such as nutrients to include, algorithm construction, and choice of reference amounts, were investigated and validated against the diet quality index HEI (59). In the validation study the HEI was regarded as a way to validate the NRF index against an "accepted independent measure of diet quality", which was done by investigating which index version that could explain the most variation in HEI (59). An NRF index including nine nutrients to encourage and three nutrients to limit (NRF9.3) based on 100 kcal or on serving size, was suggested as "a benchmark for future algorithm development" (59).

To further investigate the NRF index in a Swedish context, in 2020 Bianchi *et al* validated the NRF index on a food level against the coherence with the 2015 Swedish FBDGs (60). The aim of the study was to evaluate if a nutrient density index could be suitable for use in food LCA, e.g., as a nutritional-based functional unit, and to illuminate the implications of methodological aspects of index construction (60). The NRF index was chosen as the benchmark nutrient density index for further development and evaluation since it was viewed as a "robust, versatile, and validated method, suitable for incorporation in sustainability assessments" (33, 60, 61).

As part of the same research project as the study from 2020 by Bianchi *et al* (60), Study I of this thesis correspondingly and complementarily aimed to validate the NRF index and investigate the impact of methodological aspects, but on a diet level against all-cause mortality. Methodological aspects investigated were choice and number of nutrients to include in the index, the use of capping, and the use of weighting. To investigate choice and number of nutrients to include, three different versions of the index were assessed:

i) the HEI validated NRF9.3 index (59), where nine nutrients to encourage (protein, dietary fibre, vitamin A, C, and E, calcium, iron, potassium and magnesium) and three nutrients to limit (saturated fatty acids, added sugar and sodium) were included,

ii) the Sweden-adapted NRF11.3 index, where in addition to the nutrients included in NRF9.3, two nutrients indicated as at risk in the Swedish population, according to the latest national food survey of eating habits in the adult population (22), were further included (i.e., folate and vitamin D),

iii) and the NRF21.3 index, which included all nutrients with recommended intakes or maximum recommended intakes listed in the NNR 2012 that are also assessed in the national food composition database (24), i.e., in addition to the nutrients included in the NRF11.3, thiamin, riboflavin, omega-3 fatty acids, niacin, vitamin B6, vitamin B12, phosphorus, iodine, selenium and zinc were also included.

Capping of nutrient intakes, which is a method used to prevent over-emphasizing the effect of diets abundant in a few nutrients (26, 59), was also evaluated. Capping was used for nutrients to encourage, and the capping limit was set at 100% of the recommended intake. Weighting was further also evaluated by using a method applying different weights to different nutrients depending on the nutrient intake of the specific population, here the Swedish population, and the difference between reported intakes and recommended intake levels (22). Weighting can entail both adding and withdrawing weight to a nutrient in the NRF index score, depending on if the population intake of the nutrient is indicated to be above or below the recommended intake or maximum recommended intake. However, weighting was not applied for nutrients to limit where the average intake of the population was below the maximum recommended intake. Further, the use of both weighting before capping and capping before weighting were also investigated, since we hypothesized that the order of event could have an impact. An overview of the 15 versions of the NRF index investigated in Study I can be found in *Figure 2*.

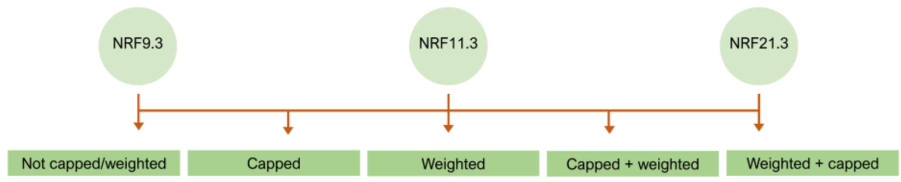

Figure 2. Overview of the 15 NRF index versions investigated in Study I.

The NRF index is calculated by dividing the estimated nutrient intake with the recommended intake or the maximum recommended intake of the individual nutrient. The sum of the intake of nutrients to limit is then subtracted from the sum of the intake of nutrients to encourage, resulting in a score that increases with increasing nutrient density. Sex- and age-specific recommended intakes and maximum recommended intakes were obtained from the NNR 2012 (24).

The NRF index version that best predicted all-cause mortality in Study I was used as the reference nutrient density index in Study II of the thesis.

4.3 THE SWEDISH HEALTHY EATING INDEX FOR ADULTS 2015

The diet quality index, the SHEIA15, was used to evaluate the study subjects' diet quality and adherence to the 2015 Swedish FBDGs in Study III of this thesis.

SHEIA15 builds upon the most recent Swedish FBDGs from 2015 and on the most recent NNR from 2012, which includes guidelines on increased intakes of vegetables, fruit, seafood, nuts and seeds, decreased intakes of red and processed meat, salt, and sugar, as well as a switch to healthy fats, wholegrains, and low-fat dairy products (13, 24). SHEIA15 was developed by Moraeus *et al* in 2020 to investigate healthy dietary habits among Swedish adolescents, and the index was then shown to be associated with higher diet quality among Swedish adolescents when the nutrient and food intakes of groups with different SHEIA15 scores were investigated (30).

To match the 2015 Swedish FBDGs, there are nine components included in SHEIA15, i.e., vegetables and fruit, dietary fibre, wholegrains, seafood, polyunsaturated fatty acids, monounsaturated fatty acids, saturated fatty acids, red and processed meat, and added sugar (30). The SHEIA15 score is calculated by dividing the nutrient and food intakes by the recommended intake or maximum recommended intake of the individual nutrient or food group, and the algorithm for SHEIA15 was originally modified based on a study by Knudsen *et al* (30, 62). An increasing SHEIA15 score indicates a higher diet quality and a higher adherence to the 2015 Swedish FBDGs, and 9 is the highest possible score due to capping (30). Reference values used for the algorithm includes the 2015 Swedish FBDGs (13), the NNR 2012 (24), as well as guidelines on wholegrains from the SFA (63). By using the recommended intake and maximum recommended intake values for adults instead of for adolescents in the algorithm, we could modify the index to be suitable to assess diet quality of adults.

4.4 DIETARY GREENHOUSE GAS EMISSIONS

The daily dietary GHGEs were assessed for each study subject in the three studies included in this thesis, indicating the climate impact of the production of their diets.

The dietary GHGEs were estimated by matching the reported intake of all the FFQ food items to data on GHGEs from food production from the Research Institutes of Sweden (RISE) Food Climate Database, expressed as kg carbon dioxide equivalents (CO_2e) per kg of edible food product at the industry gate (64, 65). System boundaries included GHGEs from primary production, processing, and transportation up to the industry gate, but excluded GHGEs from packaging and land use change. Weight changes due to hydration or dehydration of cooked foods were adjusted for, to correspond to the dietary intake data from the FFQ. GHGE data were further chosen to primarily be representative for Swedish consumption based on current production methods (66).

The RISE Food Climate Database is based on LCA methodology according to the ISO 14040 series standard (66). The database currently contains GHGE data for about 750 foods and is updated on a yearly basis. Data on GHGEs are based on available LCA data in the literature and selected based on the best available data in terms of quality, time, and geography. Method choices in terms of functional unit and system boundaries are harmonized to allow for comparison among foods. When LCA data on GHGE have been missing or been inadequate for a food product, GHGE data have been modeled by RISE to ensure quality and representation of Swedish consumption (67).

The VIP FFQ was not constructed to differentiate among food intakes important for assessing dietary GHGEs, e.g., if the reported meat intake refers to beef, pork, lamb, or game. To correct for this, assumptions about consumption were made based on national consumption statistics reflecting average Swedish consumption (68-71).

The estimated dietary GHGEs for all study subjects were adjusted for energy intake and standardized to 2000 kcal per day for women and 2500 kcal per day for men.

4.5 MYOCARDIAL INFARCTION, STROKE AND ALL-CAUSE MORTALITY

All-cause mortality during the follow-up time was selected as the health outcome for Study I and Study III. The selected health outcome for Study II was the first date of a single registered MI or stroke diagnosis during the follow-up time, and subjects with more than one outcome diagnosis, also including type 2 diabetes, at the first event were excluded from Study II (54).

Data on medical diagnoses and deaths were extracted for all study subjects from the “Patient” and ”Cause of death” registers at the National Board of Health and Welfare in Sweden (https://www.socialstyrelsen.se/statistik-och-data/register/), by the use of personal identification numbers. For Study II, ICD-9 code 410 and ICD-10 code I21 were used for MI, and ICD-9 codes 430, 431, and 433–436 and ICD-10 codes I60, I61, I63 and I64 were used for stroke (54).

The selection of MI and stroke diagnoses as representatives for dietary-related health outcomes in Study II was informed by that the Public Health Agency of Sweden states in their annual reports that circulatory diseases are the leading cause of death in Sweden, and they choose to monitor MI and stroke as indicators to follow this in the population (72). Further, a recent report from the Swedish Institute for Health Economics showed that 46% of ischaemic heart disease cases and 15% of stroke cases were associated to dietary habits, and that unhealthy dietary habits was the primary risk factor for both ischaemic heart disease and stroke, which demonstrates the relevance of choosing CVDs as health outcomes in our analyses in Study II (21).

4.6 STATISTICAL ANALYSIS

All statistical tests were performed using SPSS versions 25, 26, and 28 (IBM SPSS Statistics). All statistical analyses were stratified by gender. An overview of the statistical analyses used in the three studies included in the thesis can be found in *Table 2*.

Table 2. Overview of the statistical analyses of the studies included in the thesis

Study	Aim	Statistical analyses
I	a. Evaluate the NRF index against all-cause mortality. b. Examine the association between dietary nutrient density and dietary GHGEs, and all-cause mortality.	Cox proportional hazards regression evaluating the all-cause mortality HRs and 95% CIs between: a. Subjects classified into quintiles according to the 15 different versions of the NRF index scores b. Subjects classified into higher/lower NRF score and higher/lower dietary GHGEs, based on median values
II	a. Examine the association between the NRF index, and MI and stroke. b. Examine the association between dietary GHGEs, and MI and stroke. c. Examine the association between dietary nutrient density and dietary GHGEs, and MI and stroke.	Cox proportional hazards regression evaluating the MI and stroke HRs and 95% CIs between: a. Subjects classified into quartiles according to the NRF index scores b. Subjects classified into quartiles according to the dietary GHGEs c. Subjects classified into higher/lower NRF score and higher/lower dietary GHGEs, based on median values
III	a. Assess the association between SHEIA15 and all-cause mortality. b. Assess the association between SHEIA15 and dietary GHGEs.	a. Cox proportional hazards regression evaluating the all-cause mortality HRs and 95% CIs between subjects classified into quintiles according to the SHEIA15 scores b. Non-parametric Kruskal-Wallis one-way ANOVA test and Dunn post hoc test with significance values adjusted by the Bonferroni correction for multiple tests testing differences in dietary GHGEs between subjects classified into quintiles of SHEIA15 scores

Abbreviations: CI, confidence interval; GHGEs, greenhouse gas emissions; HR, hazard ratio; MI, myocardial infarction; NRF index, Nutrient Rich Foods index; SHEIA15, Swedish Healthy Eating Index for Adults 2015.

The categorization of study subjects into four groups based on higher/lower dietary nutrient density and higher/lower dietary GHGEs in Study I and Study II is illustrated in *Figure 3*.

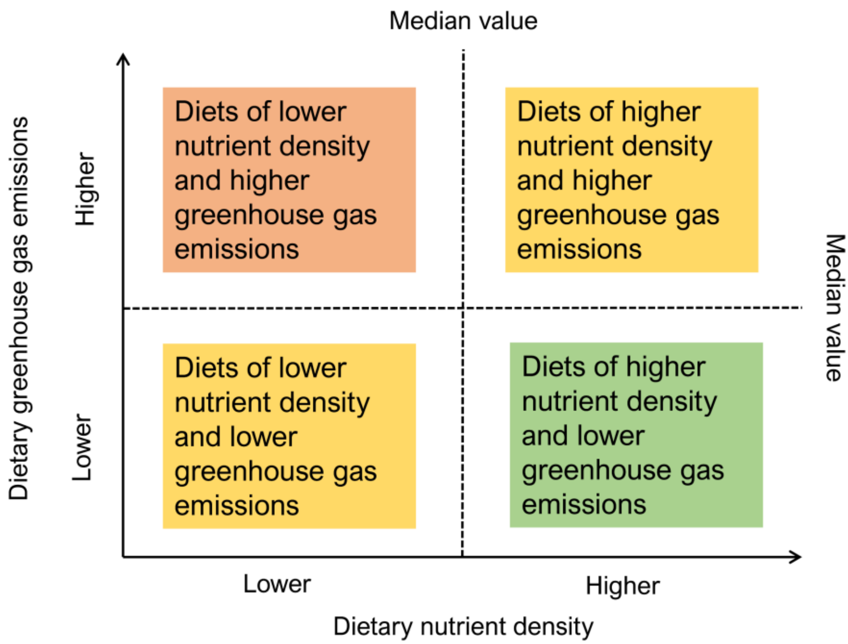

Figure 3. Classification of four groups based on the dietary nutrient density and dietary greenhouse gas emissions of the study subjects' diets. The figure is adapted from figures in Study I and Study II.

The potential confounders adjusted for in the multivariable Cox proportional hazards regression analyses were variables collected during the baseline VIP physical health screening and by the baseline health and lifestyle questionnaire:

Study I: age (continuous variable), age^2 (continuous variable), BMI (continuous variable, calculated by weight in kg divided by height in m^2), educational level (three levels: basic; high school; and university), physical activity (four levels: inactive; moderately inactive; moderately active; and active) (73), smoking status (three groups: currently smoking; have smoked; do not smoke), and year of study participation (continuous variable).

Study II: age, age^2, BMI, educational level, physical activity, smoking status, whether a close relative has had an MI or a stroke before the age of 60 years ("yes"/"no", "don't know" treated as missing), and year of study participation.

Study III: age, age^2, BMI, educational level, physical activity, smoking status, and year of study participation.

Potential confounders were selected based on similar analyses in previous literature, especially covariates that have been indicated to have confounding effects in previous research on diet-health associations within VIP.

In Study III, the purposeful selection method for model-building (74), also called the Bursac method, was performed on covariates age, age^2, BMI, educational level, physical activity, smoking status, and year of study participation. Age and year of study participation were not indicated as confounders for the women and age^2 was not indicated as a confounder for the men by the Bursac method. All other covariates (BMI, educational level, physical activity, smoking status, and year of participation for men) were suggested as possible confounders. The results of Study III are based on Cox regression models including all covariates that were indicated as potential confounders by the Bursac method overall for women and/or men.

Age was further adjusted for by also ranking by age group at baseline (35–44 y, 45–54 y, and 55–65 years) when categorizing the study subjects for all studies.

For Study I and Study III, the time in months between the baseline health screening and death or end of the study period (2016-12-31), was used as the time scale in the multivariable Cox proportional hazards regressions. For Study II the time in months between the baseline health screening and MI or stroke diagnosis, or end of the study period (2016-12-31), was used as the time scale in the multivariable Cox proportional hazards regressions.

To assess whether possible associations found in Study III were driven by a single component of SHEIA15, sensitivity analyses were performed excluding the components of SHEIA15 one at a time.

Dietary intakes were assessed with descriptive statistics among the four diet groups classified into higher/lower NRF index score and higher/lower dietary GHGEs in Study I and Study II, and among the quintiles of SHEIA15 score in Study III.

4.7 ETHICAL CONSIDERATIONS

Physically, the VIP screening is mostly non-invasive. Taking blood samples could possibly bring some discomfort to the participant. Also, the oral glucose tolerance test is not suitable for diabetics, and therefore participants with previously known diabetes mellitus or with fasting glucose exceeding the criterion for diabetes are excluded from the oral glucose tolerance test (52). Further, mentally and emotionally, the results from the health screening could possibly bring some discomfort if a negative health status is unanticipated information. However, as the screening is performed at the participants' local health care centers with immediate feedback by a nurse and personal follow-ups are planned if necessary (52), the participants are cared for and supported by the local primary health care providers. With the possible benefits of direct improved health at an individual level and improved public health at a societal level, the possible discomforts of taking blood samples or of negative health results, are considered outweighed.

The original VIP study was approved by the Research Ethics Committee of Umeå University, Sweden, in 1984 (nr 2424:39/84). All study participants provided a written informed consent to participate in VIP and acknowledging that the data collected during VIP would be used in future research. The participants could also withdraw from VIP at any time. For all studies using VIP data, the existing consent from the original study is used and no further consent is collected. With the large number of participants in VIP, and the large amounts of studies based on data from VIP since the start, the collection of renewed consent for every new study based on VIP material would not have been practically possible. Instead, ethical approval from Research Ethics Committees complements the written informed consent and is obtained to perform studies using VIP data. Ethical approval has therefore been obtained for all three studies included in this thesis from the Swedish Ethical Review Authority in 2017 (Dnr. 886-17) and in 2019 (Dnr. 2019-01314). Further, the VIP data are also decoded before receiving them and analyzed on group level only, and therefore individuals cannot be distinguished and the risk for integrity infringement is very low. The risks for the participants are thus small and are offset by the fact that the studies of the thesis can provide valuable information that in the long run can support the development of more sustainable dietary guidelines, benefiting both public health and environment.

5 RESULTS

Overall, the results of this thesis suggest that the NRF index can predict all-cause mortality in the study population (Study I), but for most part not MI nor stroke morbidity (Study II). Further, combined analyses of nutrient density, dietary GHGEs, and health impact, suggest that diets beneficial for both health and climate are possible (Study I), but also that diets related to lower GHGEs can be associated with negative health impacts, especially when nutrient density is disregarded (Study I and Study II). Moreover, diet quality investigated by SHEIA15 predicted both all-cause mortality and GHGEs from diet, indicating that following the 2015 Swedish FBDGs can bring benefits both to public health and climate change (Study III).

For Study I and Study III, the median and maximum follow-up times from baseline to death or study end were for women 16.0 years and 25.9 years, respectively, and for men 14.7 years and 26.8 years, respectively. For Study II, the median and maximum follow-up times from baseline to MI or stroke diagnosis or study end were for women 15.7 years and 25.9 years, respectively, and for men 12.8 years and 26.8 years, respectively.

Crosstabulations of the classifications of the study subjects into quintiles of NRF11.3 index score and quintiles of SHEIA15 score can be found in *Table 3* (women) and *Table 4* (men).

Table 3. Crosstabulation of the classifications of VIP women into quintiles (Q) of NRF11.3 index score and quintiles of SHEIA15 score.

		Quintiles of SHEIA15, n				
		Q1	Q2	Q3	Q4	Q5
Quintiles of NRF11.3 index, n	Q1	5878	2464	1062	357	62
	Q2	2461	3129	2396	1384	456
	Q3	1071	2390	2693	2356	1315
	Q4	358	1392	2371	2954	2751
	Q5	55	451	1303	2775	5240

Table 4. Crosstabulation of the classifications of VIP men into quintiles (Q) of NRF11.3 index score and quintiles of SHEIA15 score.

		Quintiles of SHEIA15, n				
		Q1	Q2	Q3	Q4	Q5
Quintiles of NRF11.3 index, n	Q1	5641	2474	1017	347	50
	Q2	2342	3132	2471	1269	317
	Q3	1055	2283	2753	2436	1004
	Q4	405	1254	2284	3090	2498
	Q5	86	388	1006	2389	5660

5.1 STUDY I

In Study I, methodological aspects of constructing a nutrient density index were investigated. In total, 15 versions of the NRF index were evaluated against all-cause mortality, testing the choice and number of nutrients included, the use of capping, as well as the use of weighting. To determine which index version best predicted all-cause mortality, the trend consistency of all-cause mortality HR estimates were compared among the different versions. Importantly, all NRF index versions were able to predict all-cause mortality and thus suitable to evaluate diet quality; however, for women the Sweden-adapted NRF11.3 index stood out as the best. Further, the application of capping to the nutrients included in the index improved the HR estimate trend consistency for both women and men. However, the application of weighting resulted in marginally improved HR estimate trend consistency in men and had no effect for women. Hence, the NRF11.3 index with the application of capping was used in further analyses in both Study I and Study II.

Study I further examined the association between diets with different levels of nutrient density (estimated by the NRF11.3 index) and GHGEs, and all-cause mortality. Importantly, for women, a lower all-cause mortality hazard was indicated for the "most desirable" diet scenario group (higher nutrient density, lower GHGEs), compared with the "least desirable" diet scenario reference group (lower nutrient density, higher GHGEs). Also, the women with diets of higher nutrient density and higher GHGEs had a lower all-cause mortality hazard, compared to the reference group. The associations found for women were not found for men. Instead, importantly for men, the diet group with lower nutrient density and lower GHGEs indicated a higher all-cause mortality hazard, compared with the reference group having the same level of dietary nutrient density but higher dietary GHGEs.

5.2 STUDY II

In Study II, the associations between dietary nutrient density, estimated by the NRF11.3 index, and MI and stroke morbidity were examined. Importantly, for women, the two quartiles with the highest nutrient density indicated lower stroke hazards compared with the quartile with the lowest nutrient density. However, the lowest stroke hazard for women was found in the second highest quartile of nutrient density. No association between nutrient density and stroke was found for men, and no association between nutrient density and MI was found for neither women nor men. Hence, the results from Study I suggesting that the NRF11.3 index is a useful predictor of all-cause mortality, could not be confirmed in Study II based on associations with specific dietary-related health outcomes.

Study II also examined the associations between dietary GHGEs, and MI and stroke morbidity, to further examine the negative association between dietary GHGEs and health outcomes indicated in Study I. Importantly, for men, a consistent trend of higher MI HRs with lower dietary GHGEs was indicated. No association between dietary GHGEs and MI was found for women, and no association between dietary GHGEs and stroke was found for neither women nor men.

Further, Study II examined the associations between diets with different levels of nutrient density (estimated by the NRF11.3 index) and GHGEs, and MI and stroke morbidity. No similar association was found between diets of higher nutrient density and lower GHGEs and positive health outcomes, as that found in Study I. However, like Study I, for men, the diet group with lower nutrient density and lower GHGEs indicated a higher MI hazard, compared with the reference group having the same level of dietary nutrient density but higher dietary GHGEs.

5.3 STUDY III

In Study III, the association between SHEIA15 and all-cause mortality was assessed, correspondingly examining the health impact of increasing diet quality measured as increasing adherence to the 2015 Swedish FBDGs. For women, a consistent trend of decreasing all-cause mortality HRs with increasing diet quality was indicated. For men, a similar association as that of women was found, however the trend was less consistent.

Study III further assessed the association between SHEIA15 and dietary GHGEs, examining if an increased adherence to the 2015 Swedish FBDGs was associated with lower dietary GHGEs. For both women and men, a consistent trend of lower dietary GHGEs with higher adherence to the 2015 Swedish FBDGs was indicated. However, sensitivity analyses excluding the components of SHEIA15 from the index one at a time indicated smaller or non-existent differences in levels of dietary GHGEs between the highest and lowest quintile of SHEIA15 when the component red and processed meat was excluded.

5.4 DIETARY INTAKE

In Study I and Study II, reported dietary intakes per 2000 kcal for women and per 2500 kcal for men were compared among the four groups created based on dietary nutrient density and dietary GHGEs. Dietary patterns were indicated for: i) women and men with higher nutrient density, i.e., higher reported intakes of wholegrain products, low-fat dairy products, vegetables, and fruit; ii) women and men with lower nutrient density, i.e., higher reported intakes of high-fat dairy products and high-sugar products; and iii) women and men with higher versus lower dietary GHGEs, i.e., higher versus lower reported intakes of animal-based food products.

In Study III, the reported intakes of all the food and nutrient components in SHEIA15 per 2000 kcal for women and per 2500 kcal for men were examined among the quintiles of SHEIA15. As expected, increased intakes of vegetables and fruit, dietary fibre, wholegrains, fish, and polyunsaturated fatty acids, as well as decreased intakes of red and processed meat, added sugar and saturated fatty acids, with an increasing SHEIA15 score were indicated among both women and men. However, the intake of monounsaturated fatty acids decreased with increasing SHEIA15 score.

6 DISCUSSION

The overall aim of the studies in this licentiate thesis was to assess dietary quality and greenhouse gas emissions of self-reported diets, and the association with health outcomes, in a population-based cohort in northern Sweden. The thesis indicated both potential co-benefits and trade-offs between dietary quality, dietary GHGEs, and health outcomes. Furthermore, two indices assessing different aspects of dietary quality were suggested as predictors of all-cause mortality, of which one was further suggested as a predictor of dietary GHGEs.

The main findings of the studies in this thesis, as well as the methodological considerations, are discussed below.

6.1 MAIN FINDINGS

The NRF index, a predictor of health outcomes?

The NRF index is a nutrient density index developed to capture the nutrient density of food products (59). At a food product level, the index has been validated against the diet quality index HEI in an American context (59), and against the 2015 Swedish FBDGs in a Swedish context (60). Due to the construction of the algorithm, the NRF index has further been suggested as a nutrient density index applicable to diets (33). However, to use it as a dietary quality index, validation has been recommended (59). Hence, one of the aims of Study I was to assess if the NRF index, used to estimate the nutrient density of diets, could be a predictor of all-cause mortality, and hence a proxy for healthy diets (59).

Study I indicated that the NRF index could be a predictor of all-cause mortality by indicating trends of lower HRs of all-cause mortality with increasing dietary nutrient density in the study population. By evaluating different methodological choices related to the construction of the algorithm, Study I could also identify important methodological considerations and suggest an index version especially capable of predicting all-cause mortality in the study population. The choice and number of nutrients included, especially for women, as well as the application of capping, were suggested as important methodological considerations. Eventually the Sweden-adapted NRF11.3 index with the application of capping to nutrients, but without the application of weighting, was indicated as the best predictor of all-cause mortality in the study population in Study I.

All-cause mortality includes all deaths, i.e., also deaths unrelated to dietary habits. Hence, one of the aims of Study II was to confirm the results of Study I by examining the association between the NRF index and health outcomes more specifically related to dietary habits. Since circulatory diseases cause approximately a third of all deaths and are the leading causes of deaths in Sweden (72, 75), and since unhealthy dietary habits have been indicated as the primary risk factor for both ischaemic heart disease and stroke in Sweden (21), MI and stroke incidences were considered as suitable representatives for dietary-related health outcomes in Study II. Nevertheless, Study II could not confirm the association found between the NRF11.3 index and all-cause mortality in Study I. No association was found between the NRF11.3 index and MI, and only an inconsistent association was found between the index and stroke among women in Study II.

Similar results as that of Study I and Study II were found in a Dutch study from 2014 by Streppel *et al* (76). The Dutch study aimed to examine the association between the NRF9.3 index scores of self-reported diets and major CVD events and all-cause mortality in a community-based cohort study. Like Study I and Study II, the NRF9.3 index was inversely associated with all-cause mortality, but no association was found between the NRF9.3 index and incidence of CVD (76).

The VIP FFQ was constructed to capture dietary intakes important for CVDs, such as fat quality and wholegrain intake (19, 21), and the FFQ should hence be able to differentiate among levels of those important dietary intakes. The NRF11.3 index further included nutrients that can be found in food products important for CVDs, such as e.g., dietary fibre, vitamin C, vitamin E, folate and magnesium that are found in considerable amounts in fruit, vegetables, and wholegrains. Still, a high sodium intake is one of the most important dietary intakes for developing CVDs (19, 21). Even though salt intake is included in the NRF11.3 index, it is a dietary intake that is challenging to capture with dietary assessments like the FFQ in VIP, possibly impacting the ability to identify any significant associations. Further, since only the baseline dietary intake was used to calculate the NRF11.3 index in the current studies, changes in dietary habits during the follow-up time was not considered. This may have impacted the ability to identify any associations as well.

Nevertheless, if a dietary quality index cannot predict health outcomes known to be related to dietary habits, can it be viewed as a suitable index to capture quality of diets? Dietary nutrient density indices provide more and composite information of dietary nutrient composition than what dietary data on separate nutrients can provide. However, the ability of nutrient density indices to fully capture healthfulness of diets have been questioned before, and hybrid indices including food groups in addition to nutrients have been suggested as the path forwards (77). In Study II it was speculated that a hybrid index including both nutrients and foods could possibly predict dietary-related CVDs better than do indices including only nutrients, since earlier acknowledged dietary-related risk factors for CVD mortality and morbidity included both nutrients and foods (19, 21). Study III originated from these speculations.

Co-benefits and trade-offs between nutrient density, dietary GHGEs, and health outcomes

Study I and Study II further examined the association between diets with different levels of nutrient density and GHGEs, and all-cause mortality as well as MI and stroke morbidity. By categorizing study subjects based on both dietary nutrient density and dietary GHGEs, a combined assessment of nutrient density and dietary GHGEs and associations with health impacts could be performed. Hence, potential co-benefits and trade-offs between dietary quality, dietary GHGEs, and health could be identified.

Study I indicated an association between diets of lower GHGEs and higher nutrient density (estimated by NRF11.3), and lower all-cause mortality HRs, for women. This "most desirable" diet scenario was compared with the "least desirable" diet scenario of diets of higher GHGEs and lower nutrient density. Also for the women in the diet scenario group with higher nutrient density but the same level of dietary GHGEs as the reference group, a lower all-cause mortality hazard was indicated. This suggests potential co-benefits between nutrient density, dietary GHGEs, and health for women. Still, it seems as though the driving factor of the association with health for women is primarily dietary nutrient density and not dietary GHGEs. For men no associations with all-cause mortality were found for the two diet scenario groups with higher nutrient density. Hence, further studies investigating by what means men can achieve nutritious, climate-sustainable, and healthy dietary habits are needed. Further, in Study II, the indicated associations with all-cause mortality for women could not be reproduced with MI and stroke.

In both Study I and Study II, associations were found between diets with lower GHGEs and lower nutrient density, and higher all-cause mortality and MI HRs among men. This association was found by comparison with the reference diet scenario group with diets of the same level of nutrient density, but with higher GHGEs. By separately investigating the association between dietary GHGEs and MI apart from nutrient density, an association was similarly found of decreasing dietary GHGEs and increasing HRs of MI. These associations suggest potential tradeoffs between dietary GHGEs and health for men. Nevertheless, since the associations between dietary GHGEs and negative health effects in the combined analyses with nutrient density were not indicated among men with diets of higher nutrient density and lower GHGEs in Study I and Study II, the importance of taking the dietary quality of climate-sustainable diets into consideration is suggested.

The indicated associations between lower dietary GHGEs and negative health outcomes could possibly explain why the indicated association between the NRF11.3 index and all-cause mortality for men in Study I was null when dietary GHGEs was included as a factor in the analyses – that the negative association between dietary GHGEs and all-cause mortality was stronger than the association between nutrient density and all-cause mortality for men and hence neutralized it.

Opposite results to those of Study I and Study II were indicated in a study including cohort diet data from ten European countries, i.e., associations between diets of higher GHGEs and higher all-cause and cause-specific mortality hazards were found (78). However, adjustment of energy intakes in the analyses instead suggested null associations or more similar results to those of Study I and Study II (78). Still, more studies are needed to understand the factors driving the association between lower dietary GHGEs and negative health outcomes.

The SHEIA15, a predictor of health outcomes and dietary GHGEs?

Moving forward from nutrient density indices in Study I and Study II, a hybrid diet quality index, including both nutrients and foods, was investigated in Study III. Hybrid indices of the NRF family have previously been suggested, both a theorized index building upon the Dietary Guidelines for Americans (77), and against HEI validated indices (79). However, adapting the hybrid NRF indices to a Swedish context proved challenging since adding food groups required exclusions of nutrients to decrease the risk for double counting. Therefore, an already published diet quality index based on the latest Swedish FBDGs from 2015, the SHEIA15, was included in the analyses (30). SHEIA15 has earlier been associated with higher diet quality among Swedish adolescents when the nutrient and food intakes of groups with different SHEIA15 scores were investigated (30). However, the diet quality index has yet not been assessed in an adult population, nor validated against health outcomes.

The 2015 Swedish FBDGs are in an international perspective one of the first FBDGs integrating environmental, nutritional, and public health aspects (13, 80). Hence, the aim of Study III was to assess if the diet quality index SHEIA15 could be a predictor of all-cause mortality as well as of dietary GHGEs, and hence a proxy for healthy and climate-sustainable diets.

Study III indicated that SHEIA15 could be a predictor of all-cause mortality by demonstrating trends of lower HRs of all-cause mortality with increasing SHEIA15 score in the study population, suggesting SHEIA15 as a suitable index to assess diet quality in a Swedish context. The association was stronger among women than among men. Study III further indicated a consistent trend of lower dietary GHGEs with higher SHEIA15 score, suggesting SHEIA15 as a predictor of dietary GHGEs as well. Hence, a higher adherence to the 2015 Swedish FBDGs is indicated as beneficial for both health and climate, suggesting that including environmental, nutritional, and public health aspects in national FBDGs is possible and advantageous. Still, sensitivity analyses suggested that the indicated association between SHEIA15 and dietary GHGEs were mostly driven by the component red and processed meat.

Previous studies from the US, the Netherlands, Spain, Australia, and China, assessing associations between diet quality indices estimating adherence to dietary guidelines and health outcomes have found similar associations as that of Study III, i.e., lower all-cause mortality with higher adherence to dietary guidelines (81-86). Further, a Swedish study assessing the associations between dietary GHGEs and adherence to the NNR 2012 found that the overall adherence to Nordic dietary guidelines was better among participants with lower compared with higher dietary GHGEs (87). Also, similar to Study III, a Dutch cohort study from 2017 of self-reported diets indicated that a better adherence to WHO and Dutch dietary guidelines, estimated by the WHO's Healthy Diet Indicator (HDI) and the Dutch Healthy Diet index 2015 (DHD15-index), were associated with lower all-cause mortality and moderately lower dietary-related GHGEs and land use (88). Thus, diet quality indices estimating adherence to dietary guidelines are often effective in predicting health outcomes, and a higher adherence to FBDGs suggests benefits for climate change.

As noted previously, associations found between the NRF11.3 index and all-cause mortality in Study I could not coherently be confirmed with MI or stroke incidence in Study II. However, SHEIA15 could possibly have the ability to predict dietary-related CVDs better than the NRF11.3 index by including previously acknowledged dietary risk factors for CVDs, such as wholegrains, fruit and vegetables, poly-unsaturated fatty acids, and processed meat (19, 21). Also, another diet quality index based on the 2015 Swedish FBDGs, the SDGS, including the dietary components dietary fibre, fish, fruit and vegetables, added sugar, and red and processed meat, indicated inverse associations between the SDGS and total and ischaemic stroke (31). Hence, the association found between SHEIA15 and all-cause mortality in Study III should be confirmed by assessing the association between SHEIA15 and health outcomes more specifically related to dietary habits, to ensure its effectiveness at capturing healthy dietary patterns related to lower NCD incidence.

6.2 METHODOLOGICAL CONSIDERATIONS

Dietary intake data

The dietary intakes used to estimate nutrient density, diet quality, and dietary GHGEs for all analyses in this thesis were derived from the self-reported food frequencies from the VIP semiquantitative FFQ.

The 84-question VIP FFQ has been validated against 24-hour recalls, indicating dietary intake frequencies of good reproducibility and on a level of validity similar to other prospective cohort studies (55). Still, moderately higher intake frequencies of vegetables, fruit, bread, cereals, rice, potatoes, pasta, and dairy products, and lower intake frequencies of fish, meat, alcoholic beverages, and sweets, were recorded by the FFQ compared to the 24-hour recalls. Also, lower estimated intakes of vitamin C, dietary fibre, beta-carotene, and retinol, and higher estimated intakes of cholesterol and sucrose were recorded by the FFQ compared to the 24-hour recalls (55). Hence, dietary GHGEs could have been underestimated, and dietary quality could have been either over or underestimated, impacting the results.

The original 84-question FFQ was over the years replaced with 64-66-question versions for financial and practical reasons. The FFQ versions used in this thesis to capture the participants' dietary habits have mostly been the same, or the intakes have been harmonized across versions, which means that the dietary intake estimates over the years are comparable.

All the FFQ versions used in VIP are short, with only 64–84 questions. Hence, the FFQ is likely unable to capture the participants' whole diets (46), thus underestimating total intake as well as dietary quality and dietary GHGEs Further, as new food products constantly emerge on the market, the static FFQ has likely also captured less and less of the participants' dietary habits over the years, as indicated by lower total energy intake concurrent with higher BMI when 10-year repeated measures were compared (89). Further, like all reported dietary data, data from FFQs also suffer from misreporting. Misreporting has previously been shown to be selective, with sugar and fat as dietary components more commonly underreported (49, 50). To partly correct for expected misreporting related to energy intake, energy adjustments of nutrient and food intakes have been performed as previously suggested (46, 57). However, due to possibly selective misreporting, the estimation of dietary quality could have been impacted.

Thanks to its retrospective design, FFQs can assess habitual dietary intake, which is necessary for assessing associations between diet and health outcomes with long latency periods. FFQ dietary data are also considered good for ranking individuals based on their dietary habits (45), and the VIP FFQ is hence deemed able to assess dietary intake for the main analyses of the studies in the thesis. Yet only the baseline data for dietary intake were included, and changes in dietary habits or other lifestyle habits during the follow-up time could have impacted the associations. Still, since chronic diseases such as CVDs have long latency periods, using baseline data ensured that sufficient time had passed between exposure and outcome.

Furthermore, since the purpose of VIP has been to reduce CVD morbidity and mortality, the FFQ was developed to differentiate among various dietary habits important for CVD. However, in several instances the FFQ combined foods with various GHGEs in one question, and hence dietary intakes critical for estimating dietary GHGEs could not be differentiated. Assumptions based on national consumption statistics were applied to partly correct for this issue; however, the estimation of dietary GHGEs is likely impacted by this inability to differentiate between some important dietary intakes. For food groups with lower GHGEs, this probably had only a small impact on the estimations of dietary GHGEs. However, for food groups with higher GHGEs, such as meat, this may have impacted the estimations of dietary GHGEs considerably.

Life-cycle assessment data

LCA is a comprehensive, systematic and internationally standardized methodology used to quantify the environmental impact of a food product during its life cycle, i.e., from raw material to waste disposal (41). In this thesis, LCA data from previous literature, collected and processed by RISE, has been used to estimate the dietary-related GHGEs considering emissions from primary production to industry gate.

LCA is a commonly used tool for studying the environmental impacts of food products (41). However, food systems are complex and the precision with which LCA captures environmental impacts of food products varies. Regional and local differences in e.g., climate conditions, resource use, and technological development can result in environmental impacts differing greatly for one and the same food product (41, 42). LCA data also generally suffers from methodological issues, such as a focus on a limited range of foods, a limited set of impact categories (mostly climate impact), and geographical bias (41), as well as uncertainties, such as quality of input data, different methods of calculation, choice of functional unit, system boundaries and allocations (42, 44). Also concerns on how food LCA results are aggregated have been raised, for example if LCA data for a specific food item is used to represent a broader food category in the case of data limitations (44). These aspects can generally impact the quality and representativeness of the LCA data.

The RISE Food Climate Database is updated yearly and the included GHGE data are selected based on the best available LCA data from the literature in terms of quality, time, and geography. Method choices are harmonized in terms of functional unit and system boundaries, and the data has been modeled with the aim to represent Swedish consumption based on current production methods (67). Still, the GHGE data from RISE is general, i.e., not connected to products of specific producers, and can hence only be viewed as rough estimations (66). Further, the system boundaries included GHGEs from primary production, processing, and transportation up to the industry gate, but excluded GHGEs from packaging and other activities later in the food chain, as well as land use change. Even though most GHGEs arise from the included system boundaries (15, 17), the emissions from the food products whole life cycle are not included, and the dietary GHGEs may therefore be underestimated.

The GHGE data used to estimate daily dietary GHGEs for the study subjects are from versions of the RISE Food Climate Database from 2018 and 2019, since it was the most representative LCA data available at the time of the research project in which the studies of this thesis are included. Hence, the GHGE data does not match the time period during which the dietary intake data were collected (1990–2016). During the time period of the included VIP study subjects, GHGEs of food products may have changed due to e.g., changes in production methods and origin. However, since the focus of the studies in this thesis was the impact of food intake and dietary patterns, it was deemed most suitable to base the assessments of dietary GHGEs on LCA data representative for current production methods, thus matching existing policy goals and recommendations, compared with production systems used historically.

Dietary quality indices

The results of this thesis indicate that the NRF11.3 index and the SHEIA15 capture slightly different dietary habits, since the categorization into quintiles and the HR estimates in the Cox regression analyses differed between Study I and Study III. Possible explanations for this are that the indices differ in both components and algorithm.

The NRF11.3 index is a nutrient density index and estimates a score based on nutrients (plus added sugar and salt). The SHEIA15 is a diet quality index and estimates a score based on both nutrients and food groups. Common components for both indices are dietary fibre, saturated fatty acids and added sugars. Even though the NRF11.3 index includes nutrients abundant in the food groups included in the SHEIA15, some discrepancies exist. SHEIA15 mostly favors plant-based foods, such as vegetables, fruit, and wholegrains, and has a focus on fat quality. The NRF11.3 index instead favors micronutrients and macronutrients found in both plant-based and animal-based foods. Hence, for example red and processed meat is treated as a negative component in SHEIA15, but provides nutrients treated as positive in the NRF11.3 index, such as protein, iron, magnesium, and potassium. Another aspect that differs between the indices is that of capturing food matrix effects. Capturing the healthfulness of diets goes beyond nutritional content, and interactions among nutrients within a food or among foods in diets constitutes important considerations (24, 35).

In addition to components, the algorithm used for the NRF11.3 index and the SHEIA15 differs as well. The NRF11.3 index is calculated as the sum of the ratios (intake/recommended intake) of positive components minus the sum of the ratios (intake/maximum recommended intake) of negative components, and hence the NRF11.3 score has no maximum or minimum limit. SHEIA15 instead produces a score between zero and nine since the index is calculated as the sum of the ratios of positive components (intake/recommended intake) as well as ratios of negative components (1 – intake/maximum recommended intake). Both indices apply capping. However, in SHEIA15 all values <0 and >1 for each component are capped. For NRF11.3, only the values for positive components >1 are capped, and for nutrients with no upper limit in the NNR 2012 (dietary fibre) no capping is applied. This entails that negative components can have a greater impact on the score when estimated by the NRF11.3 index than when estimated by SHEIA15.

Many different nutrient density indices as well as diet quality indices exist. Choices made regarding construction of these indices, such as food items or nutrients included, cut-off values used, and scoring method, have previously been deemed subjective and arbitrary (36). In Study I, several methodological considerations were demonstrated to impact the association between nutrient density and all-cause mortality. Comparing the NRF11.3 index and SHEIA15 further indicate that choices made regarding the construction of dietary quality indices can possibly impact results. Dietary quality indices need to be carefully selected and evaluated to ensure that they quantify what they are meant to quantify (90).

Statistical aspects

Since the studies in this thesis are observational studies, it is not possible to establish that the associations indicated between dietary patterns and health outcomes are causal.

The possible confounders adjusted for in the Cox regression analyses were selected based on similar analyses in previous literature, especially covariates that have been indicated to have confounding effects in previous research on diet-health associations within VIP. The purposeful selection method for model-building (74), also called the Bursac method, was further tested in Study III, indicating that including two covariates for age in the Cox analyses was redundant, and that year of participation was not a confounder for women. All other covariates (BMI, educational level, physical activity, smoking status, and year of participation for men) were suggested as possible confounders by the Bursac method. Nevertheless, residual confounding effects of covariates adjusted for, as well as important covariates unadjusted for, could have an impact on the observed associations.

Further, since the dataset used for Study II was originally prepared for a study investigating the association between intake of dairy products and cardiometabolic diseases by Johansson *et al* (54), the exclusion performed regarding participants who emigrated or immigrated during the follow-up period may have impacted the generalizability of the results from Study II. Furthermore, the health outcome selected for Study II was the first date of a single registered MI or stroke diagnosis during the follow-up time, and participants with multiple outcomes were excluded. This could have further impacted associations, due to that data are treated as if participants die from MI or stroke, when being diagnosed with one of the health outcomes instead can hasten the other outcome. Nevertheless, sensitivity analyses indicated that competing risks were not present.

Also, multiple testing was adjusted for in the analyses of differences in dietary GHGEs among subjects classified into quintiles of SHEIA15 score by the Bonferroni correction for multiple tests in Study III. However, multiple testing was not adjusted for in the Cox regression analyses, and the p-values from the Cox regression analyses should hence be interpreted with caution.

Categorizations of study participants were performed based on dietary quality scores and dietary GHGEs values for all analyses. These categorizations were based on rankings into two groups, quartiles or quintiles based on the population-specific median or percentile values. Hence, no conclusions can be drawn regarding how much more nutrient dense or how much more climate-friendly the assessed diets are in one group compared to another, and the assessed diets cannot be stated as “healthy” or “nutrient dense” or “climate-sustainable”, or the opposite. To truly interpret how meaningful the variations in nutrient density, diet quality and dietary GHGEs are, applying meaningful cut-offs such as recommendations or physiological limits to define the groups would have been helpful and suitable. However, no functional limits have been identified for the NRF11.3 index score or SHEIA15 score. Also, with respect to GHGEs, when testing the suggested sustainable limits of approximately 0.6–0.7 tonnes CO_2e per year and person from food from the WWF in Study I (91, 92), they were deemed unfeasible for our analyses due to too unbalanced groups. The strategy to categorize study subjects into several groups based on a continuous variable is a common approach in nutritional research to handle measurement errors connected to dietary intake estimates, and it is also an objective way to categorize participants that facilitates interpretation of results, as well as useful when it is unknown if the association is linear. To enable combined assessments of dietary nutrient density and dietary GHGEs, cross-tabulation based on median values was further deemed necessary to generate a feasible number of study subjects in each group. However, it is acknowledged that there is a loss of information when a continuous variable is split into a few categories (93).

Sustainability aspects

Nutrition, health, and climate impact are central aspects of sustainable diets; however, other important aspects of sustainable diets are not taken into consideration in this thesis.

Climate impact is the environmental aspect of food products most commonly estimated in food LCA studies (41). The larger availability of food LCA data for climate impact compared to other environmental impact categories is an advantage when assessing complete diets as it allows for a higher precision in the assessment (18). However, it is also known that goal conflicts may exist between environmental indicators. For example, raising ruminants is associated with large GHGEs resulting in high climate impact per kg of meat, on the other hand grazing animals may have positive effects on the biodiversity (94). By including other environmental aspects in the analyses of this thesis, such as water use or biodiversity, classifications of diets could have been changed substantially, impacting associations. Also including the important aspect of food waste, as well as including further aspects of sustainable diets, such as e.g., affordability, could have changed classifications of diets further, also impacting associations. Even though more holistic sustainability assessments is an emerging trend in the research field of combined health and environmental assessment of food, it is still common that only a limited set of sustainability indicators are used (95). Using a holistic approach when assessing sustainability of diets is advised (5).

Further, since energy adjustments are applied to all food intakes of the study subjects, the carbon footprint of absolute intakes of food is an aspect not assessed. Overconsumption of food impact both health and environment, and to eat no more than needed to maintain a healthy body weight is an action to reduce dietary GHGEs identified by Garnett *et al* (15), and it is further addressed by the 2015 Swedish FBDGs for both health and environmental aspects (13, 25).

7 CONCLUSIONS AND FUTURE PERSPECTIVES

The results of the nutrient density index assessments in Study I of this thesis suggested that the NRF index, assessing nutrient density of self-reported diets, can predict all-cause mortality in a Swedish population. The Sweden-adapted NRF11.3 index with the application of capping was deemed particularly suited to estimate quality of Swedish diets, as an increasing dietary nutrient density was associated with lower mortality hazard ratios. However, the association indicated between the NRF11.3 index and all-cause mortality could for most part not be confirmed with the dietary-related health outcomes MI and stroke in Study II. Hence, the capability of the NRF index to truly assess dietary quality can be questioned. A future perspective raised by Study II was that a hybrid dietary quality index, including both nutrients and foods, could potentially better predict health outcomes than could an index including only nutrients. This was hypothesized since the known dietary-related risk factors for health outcomes include both nutrients and foods. This hypothesis was examined by Study III.

The results of the combined dietary assessments of nutrient density and GHGEs in Study I showed that diets with a higher nutrient density and lower dietary GHGEs were associated with lower all-cause mortality hazard ratios for women, indicating that diets advantageous for nutrition, health and climate are possible. However, the same association was not found for men, and studies are thus needed to investigate by what means men can achieve dietary habits positive for both health and climate.

The results of the combined dietary assessments of nutrient density and GHGEs further showed, in both Study I and Study II, that diets with lower nutrient density and lower GHGEs were associated with higher all-cause mortality and higher MI hazard ratios in men. These associations were further supported by results in Study II indicating that decreasing dietary GHGEs were associated with increasing MI hazard ratios. Hence, negative health impacts of diets beneficial for climate may exist, especially when nutrient density is disregarded. However, further examination is needed to determine the factors underlying the found associations. To perform such further examination, dietary intake data that better differentiate among food intakes important for the GHGEs of food consumption, such as type of meat, are required. Especially the health outcomes of self-reported diets expressly selected due to lower GHGEs would be interesting to examine.

Moving from dietary nutrient density to diet quality, the results of Study III suggested that the diet quality index SHEIA15 can predict both all-cause mortality and dietary GHGEs in a Swedish population. SHEIA15 is hence deemed suitable to estimate the quality of Swedish diets. Since SHEIA15 builds upon the 2015 Swedish FBDGS, the results of Study III also indicate that following the Swedish dietary guidelines is associated with benefits both to health and climate.

Since the studies in this thesis are observational studies, it is not possible to establish that the associations indicated between dietary patterns and health outcomes are causal. Further, the findings from this thesis should be investigated in other prospective cohorts, preferably in cohorts having repeated measurements of dietary intake captured by dietary assessment methods able to differentiate among dietary intakes important for estimating dietary quality and dietary GHGEs. Nevertheless, the studies of this thesis have contributed to the constantly growing interdisciplinary research field situated between nutritional epidemiology and food environmental research, by validating dietary quality indices to be used with other sustainability indicators in broad sustainability analyses of Swedish dietary patterns, as well as by indicating potential synergies and trade-offs between dietary quality, dietary climate impact, and health impact of Swedish diets.

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