

Sustainability in the National School Lunch Program: Balancing environmental impacts, nutritional quality, economic costs, and student acceptance to improve school lunch

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Abstract

Introduction. The world food system is driving climate change and environmental degradation while contributing to unprecedented levels of diet-related disease and economic inequalities. An essential step in resolving these issues is the widespread adoption of sustainable diets.

Sustainable diets protect ecosystems, support human health and wellbeing, and are acceptable, accessible, economically fair, and affordable. To encourage adoption, sustainable diets must be well defined, studied, and promoted. The U.S. National School Lunch Program (NSLP) offers an ideal setting to study and promote sustainable dietary patterns as it serves a large population that is establishing habits for future consumption. To do this, policy makers will need to understand the sustainability of lunches currently served and consider what changes need to be made to further improve sustainability. The *overall objectives* of this research were to evaluate the sustainability of school lunches served by the NSLP and create realistic, sustainable menus for schools using optimization modeling to guide recommendations for improvement.

Methods. Using Life Cycle Assessment (LCA) and a nationally representative sample of over 2 million lunches served by the NSLP, the first aim assessed the global warming potential (GWP) (kg CO₂ eq), marine (g N eq) and freshwater (g P eq) eutrophication potential, land use (m²a crop eq.), and water consumption (m³) of lunches served to kindergarten through twelfth grade students in the U.S. and explored the distribution of these impacts. The second aim used integer linear programming and data from Boston Public School lunch menus to design weekly lunch menus for elementary students with minimal environmental impacts which met the nutrition standards and cost constraints of the NSLP. The final aim used integer linear programming and data from Boston Public School lunch menus to create weekly lunch menus with the greatest potential caloric intake, value consumed, and nutritional quality measured using the Healthy Eating Index and lowest cost (USD), global warming potential, and water scarcity (m³ water eq.).

Results. On average, the impact per lunch served in the NSLP was 1.5 ± 0.03 kg CO₂ eq. global warming potential, 1.8 ± 0.03 m²a crop eq. land use, 0.055 ± 0.00 m³ water consumption, and 0.24 ± 0.05 g P eq. freshwater and 3.1 ± 0.00 g N eq. marine eutrophication. Across all impact categories and foods served, meat products contributed the most (28-67%) to total impacts. Compared to the highest impact lunches, the lowest impact lunches contained greater quantities of dairy, whole grains, seafood, and nuts and seeds. Menus designed with linear programming for Boston Public Schools led to major reductions in environmental impacts (15-77%) compared to current menus offered while providing adequate variety, maintaining costs, and improving nutritional quality. Menus which minimized environmental impacts offered a mix of poultry, vegetarian, and fish dishes each week and contained more vegetarian and fish options than current lunches offered. By incorporating additional priorities into optimization models, we designed sustainable menus which simultaneously increased potential consumption and nutritional quality and reduced costs and environmental impacts compared to current offerings.

Conclusions. This work highlights that through menu changes, schools can offer more sustainable menus or menus with lower costs, which are more nutritious, have lower environmental impacts, and promote greater consumption. Common themes for designing sustainable menus included offering a mix of poultry, vegetarian, and fish dishes while limiting the frequency of beef and cheese.

Acronyms and Abbreviations

BPS	Boston Public Schools
CO ₂ eq.	Carbon Dioxide Equivalent
dataFIELD	Database of Food Impacts on the Environment for Linking to Diets
DGA	Dietary Guidelines for Americans
LCA	Life Cycle Assessment
EIS	Environmental Impact Score
FAO	Food and Agriculture Organization
FCID	Food Commodities Intake Database
FICRCD	Food Intakes Converted to Retail Commodities Database
FNDDS	Food and Nutrient Database for Dietary Studies
FNS	Food and Nutrition Services
g	gram
GHG	Greenhouse gas
GWP	Global Warming Potential
HEI	Healthy Eating Index
HHFKA	Healthy Hunger Free Kids Act
ISO	International Organization for Standardization
kcal	Kilocalorie
LCI	Life Cycle Inventory
m ³	meters cubed
N eq	Nitrogen equivalent
NHANES	National Health and Nutrition Examination Survey
NSLP	National School Lunch Program
Oz. eq.	Ounce equivalent
P eq	Phosphorus equivalent
SFA	School Food Authority
SNMCS	School Nutrition Meal Cost Study
UN	United Nations
US	United States of America
USDA	United States Department of Agriculture
WFLDB	World Food Life Cycle Assessment Database
WHO	World Health Organization
WWEIA	What We Eat in America

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Chapter 1 : Introduction

Literature Review

Impacts of the Global Food System

Urgent action is needed to address the myriad of issues associated with the global food system. The most pressing of these include malnutrition, environmental degradation, and economic inequality. Although advances in agricultural production have successfully reduced global hunger for decades, in 2015 this trend began to reverse, and today nearly half of all people experience some form of malnutrition either through the lack of and/or overabundance of nutrients (FAO et al. 2020, WHO 2021). While there has been tremendous growth in agricultural efficiencies (i.e., greater yields using fewer resources) food production still uses large levels of natural resources (i.e., land and water), and contributes significantly to climate change and pollution (Rockström et al. 2020). These burdens are anticipated to escalate under current population projections and demographic changes (Tilman and Clark 2014). The food system is essential to the global economy; nearly a quarter of the world population works in the primary production of food, yet known human rights abuses due to exploitative labor practices and power imbalances are rife across the food system (OSCE 2009). Furthermore, diets which support human health are not affordable or accessible to the most vulnerable populations (FAO et al. 2020, Bank 2021). Steps to address these issues will require multifaceted approaches, with global targets, such as the sustainable development goals, helping to define clear paths forward for governments and local action.

Nutrition and Health

The food system is inextricably linked to diet quality and the global burden of disease (Gakidou et al. 2017). It is estimated that about 9% of the world population is undernourished and 40% is overweight or obese (FAO et al. 2020, WHO 2021). Malnutrition is the result of poor diet quality; both are risk factors for disease including cardiovascular disease, which is the leading cause of mortality globally (Poirier et al. 2006, HHS 2013, Asghari et al. 2017, WHO 2020). Specifically, diets high in sodium, sugar sweetened beverages, and processed meat, and low or insufficient in seafood omega-3 fatty acids, nuts and seeds, and fruits and vegetables are associated with a higher risk of cardiovascular disease and all-cause mortality (Micha et al. 2017,

Casas et al. 2018). As income and urbanization increase globally, diets are anticipated to contain more meat, empty calories, and total calories, which will further heighten the global disease burden and cost more than 3.5 trillion USD annually (Tilman and Clark 2014, Global Panel 2016).

In the United States, malnutrition is mainly observed in the form of overconsumption and is particularly concerning in children. Nearly 20% of children and adolescents are obese, with prevalences as high as 24% and 26% for non-Hispanic Black and Hispanic children respectively (CDC 2019). This puts children at risk for disease now and later in life (Lloyd et al. 2012, Park et al. 2012, Cote et al. 2013, Mohanan et al. 2014). Childhood obesity rates are partially explained by high intakes of sugar sweeten beverages, poor diet quality, and lack of physical activity (Moreno and Rodríguez 2007, Han et al. 2010, An 2017). However, improving diet quality can be particularly challenging for U.S. household experiencing food insecurity—food insecure households struggle to purchase enough food to meet each family member’s nutritional needs (Leung et al. 2014, Coleman-Jensen 2019).

Numerous interventions have shown to be effective for reducing childhood obesity in the U.S. These interventions have enhanced primary care screening and management, provided educational materials to families and individual lifestyle coaching, and worked across community settings including in schools (Bleich et al. 2013). Federal nutrition assistance programs, such as the National School Lunch Program (NSLP), have also played an important role in addressing childhood obesity as they can help to alleviate food insecurity and improve dietary quality (Kennedy and Guthrie 2016, USDA 2019).

Natural Environment

Although there have been tremendous gains in agricultural efficiencies, food production and consumption have serious environmental consequences. It is estimated that global agriculture occupies 40% of ice-free land and consumes 70% of freshwater withdrawals (Foley et al. 2005, Land and Water Division FAO 2010, IPCC 2019). Natural resource use of this degree has led to reductions in net forest coverage, losses in biodiversity, and disruptions to habitats, the hydrologic cycle, and ecosystem services such as climate and air quality regulation (Foley et al.

2005, FAO 2012, p.7, Tilman et al. 2017, IPBES 2019). Harvest rates for fishing are greater than the rate at which fish can be replenished, with one third of all fish stocks classified as overfished (FAO 2018). Additionally, applications of synthetic agricultural fertilizers contribute to nutrient cycling imbalances and lead to water quality issues, such as eutrophication (Steffen et al. 2015, Rockström et al. 2020).

The food system is a major driver of climate change, producing one third of all anthropogenic greenhouse gas (GHG) emissions (Crippa et al. 2021). Reducing emissions from the food system is essential to meeting The Paris Climate Agreement goal of maintaining warming below two degrees Celsius compared to preindustrial levels (Bajželj et al. 2014, Springmann et al. 2018, Willett et al. 2019). Food system GHG emissions are generated largely during the food production stages including fishing, aquaculture and agriculture, followed by land use and land use change (Crippa et al. 2021). Over a third of all food system GHG emissions (CO₂eq) are methane, of which enteric fermentation from ruminant production is the largest contributor (Crippa et al. 2021). The ramifications of climate change are grave and indisputable; climate change is causing extreme weather events such as heatwaves, droughts, desertification, and floods (IPCC 2019). These weather events threaten the continued production of food and have already reduced food security for certain populations.

In the U.S., food production uses over 25% of the country's total land area, 30% of freshwater withdrawals, and produces approximately 10% of all GHG emissions (Rehkamp and Canning 2018, Canning et al. 2020, EPA 2020). Over one third of the U.S. food supply is lost or wasted, as such the resources used to produce and distribute food are also wasted (Kirsten Jaglo et al. 2021). Research has estimated these impacts on the individual level and found that on average the daily adult U.S. diet produces 4.7 kg CO₂ eq., requires 25.2 MJ non-renewable energy demand, consumes 0.4 m³ blue water, and uses 9.3 m² land and 0.13 kg fertilizer (Birney et al. 2017, Heller et al. 2018).

Economic and Social

The social and economic issues of the food system can be broadly classified as concerns of human rights or food access and security. The agriculture sector employs half of the world's

labor force (ILO 2009). These agricultural workers are particularly vulnerable to human rights abuses given the nature and characteristics of the work. For crop production, agricultural work tends to be seasonal and in isolated regions, making workers highly dependent on their employer for necessities such as housing (OSCE 2009). This power dynamic, where the loss of a job could result in loss of housing and deportation for immigrants or migrants, makes workers particularly vulnerable to human rights abuses such as forced labor. Additionally, agricultural workers are paid below average wages, have minimal or no benefits and rights to organize, and are potentially unaware of their rights and other opportunities for employment (OSCE 2009). Lack of labor inspections, protective policies, and other oversight in the agricultural sector allow these violations to persist.

In the U.S., farmworkers are a marginalized labor group and conditions are similar. Most U.S. farmworkers are foreign born and over a third do not have work authorization, putting them at risk for deportation (Ornelas et al. 2021). Wages for farmworkers are low and many do not receive benefits such as employer supported health insurance (<31%) and unemployment benefits (<56%). Advocating for better working conditions or benefits can be difficult because most U.S. farmworkers do not speak English.

Much of the world's impoverished population cannot afford or access a nutritious diet (FAO et al. 2020, Hirvonen et al. 2020). The daily cost of a healthy diet is about 1.90 USD. This is above the international poverty line and exceeds the average daily food expenditures for most countries in the Global South. Access to food also remains a problem as around two billion people lack regular access to sufficient food. Even in industrialized nations such as the U.S. food access is a concern, in 2020 11% of households experienced food insecurity (Coleman-Jensen 2020).

Addressing the Issues of the Global Food System

Addressing these issues and creating a more resilient and sustainable food system will require improvements in agricultural efficiencies, protecting and restoring natural ecosystems, reducing food loss and waste, and altering diets (Garnett 2014, Searchinger et al. 2019). Examples of agricultural efficiency strategies include breeding and biotechnology to improve crop yields, better soil and water management, and increased cropping intensity to protect natural ecosystems

from cropland expansion. Altering diets and reducing food waste can lower demand for high intensity crops and products such as red meat or animal products. Several studies have explored the potential effectiveness of these strategies and found that all are necessary to meet the nutritional needs of a growing world population while maintaining warming below two degrees Celsius and staying within other planetary boundaries (Bajželj et al. 2014, Springmann et al. 2018, Searchinger et al. 2019).

Shifting global diets could be particularly important. Reducing total global consumption of all animal-based foods by 30% and shifting this consumption to plant-based foods could reduce food system GHG emissions by 6.5 GT CO₂ eq. in 2050 (Searchinger et al. 2019). This represents 59% of the food system mitigation gap needed to meet The Paris Climate Agreement goal. Other dietary change strategies have the potential to reduce the occurrence of premature mortality by 19% globally, mitigate agricultural land expansion, and curtail concerns of water scarcity (Bajželj et al. 2014, Springmann et al. 2018, Willett et al. 2019). As an essential component in confronting the challenges of the food system, this work focuses on dietary change and the concept of sustainable diets.

Sustainable Diets

Sustainable diets “are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources” (FAO 2012, p.7). Sustainable diets reflect the needs of a given location, time, and people. Therefore, there is not a singular standard sustainable diet and critical assessments and commentary on dietary sustainability include information across the domains of sustainability: nutrition and health, environment, and economic. Terminology related to sustainable diets is evolving, most research is now focusing on healthy diets from sustainable food systems. Here we use this language interchangeably.

Numerous studies have sought to identify sustainable diets by estimating the environmental impacts and the health outcomes of varying dietary patterns (Aleksandrowicz et al. 2016, Nelson

et al. 2016, Willett et al. 2019, Reinhardt et al. 2020). When focusing on environmental impacts and health outcomes, sustainable diets are generally higher in plant-based foods (e.g., vegetables, fruits, legumes, seeds, nuts, whole grains) and lower in animal-based products (particularly red meat) (Reinhardt et al. 2020). Essentially, research has found that diets with high nutritional quality are similar to diets which have lower environmental impacts.

In 2019, the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems developed evidence based scientific targets for global diets and agricultural production (Willett et al. 2019). Targets were based on extensive literature reviews and proposed limits for consumption by food group which will support human health and environmental sustainability. This work provided similar conclusion to previous research and detailed that globally diets should contain more “vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils, low to moderate amount of seafood and poultry, and no or a low quantity of red meat, processed meat, added sugar, refined grains, and starchy vegetables.”

The integration of research in health, the environment, society and culture, and economics is fundamental to identifying sustainable diets, yet most sustainable diets literature has focused on the environmental impacts and nutrient content of food while omitting issues of cultural acceptance, cost, and social impacts (Auestad and Fulgoni 2015, Jones et al. 2016, Ridoutt et al. 2017). The most commonly studied topics in the sustainable diets literature include GHG emissions, land use, consumption of animal products, energy and water consumption, agricultural management practices, local production, and nutritional quality (Jones et al. 2016).

Recent work has integrated economic and social factors by assessing the cost of sustainable diets and the risk of human rights abuses in food production. Inevitably, there are tradeoffs between the economic and social domains and environmental sustainability and health. Sustainable diets, including the targets set by the EAT-Lancet commission, are not affordable for over 1.5 billion people living in lower-middle-income and low-income countries (Hirvonen et al. 2020, Springmann et al. 2021). However, for upper-middle-income to high-income countries sustainable diets could be up to 34% less expensive than current diet costs (Springmann et al. 2021). To reduce the cost of sustainable diets for lower-income countries, dietary transitions

would need to be paired with reductions in food waste, more favorable socioeconomic development scenarios, and a more accurate accounting of savings from reduced health and climate impacts (Springmann et al. 2021). With regard to human rights, one study found that for U.S. fruit and vegetable consumption, 85% of commodity-country combinations had a high risk of forced labor, with berries and asparagus having some of the highest risks (Blackstone et al. 2021). Sustainable diets which focus on environmental impacts and health promote increased consumption of fruits and vegetables, yet these food groups might have a greater potential risk for human rights abuses within the supply chain.

The Sustainable Healthy Diets Guiding Principles developed by the United Nations (UN) provides steps for governments and other stakeholders to encourage the widespread adoption of sustainable diets (FAO and WHO 2019). The actions advise stakeholders to perform research, adopt policies, and build capacity. Research needs include country level food system analyses which estimate current consumption and dietary sustainability. In terms of policy, the guidelines suggest cohesion across diverse sectors and the adoption of national food based dietary guidelines which incorporate key themes of sustainable healthy diets. Taken together, governments should study the implications of agriculture and nutrition policy. In the U.S., researchers have examined the environmental impacts of the Dietary Guidelines for Americans (DGA) but little work has been completed on agricultural policy or the food assistance programs such as the National School Lunch Program (NSLP) (Birney et al. 2017, Blackstone et al. 2018, Chapa et al. 2020).

As part of the research required for transitioning to sustainable diets, the U.N. guiding principles called for the measurement and management of tradeoffs across goals. Tradeoffs occur when a food or food group achieves one objective while negatively impacting or failing to meet another objective. Tradeoffs and synergies have been documented across all domains of dietary sustainability (Payne et al. 2016, Perignon et al. 2017, Springmann et al. 2018, Reinhardt et al. 2020). An example of synergies appears in diets low in red meat and high in legumes as they are associated with lower GHG emissions and risks of cardiovascular disease (Willett et al. 2019). A commonly identified tradeoff is that diets rich in fatty fish threaten ocean biodiversity but are a good source of health promoting fatty acids (Mozaffarian and Rimm 2006, Brunner et al. 2008,

Mackenzie et al. 2009). As discussed previously, tradeoffs are apparent between nutrition and environmental goals and economic and social goals because of the high risk of forced labor in fruit and vegetable production and the cost of a nutritious diet. For countries to promote sustainable diets, these tradeoffs must be clearly identified and managed given the unique values and circumstances of the country.

Techniques for Identifying Sustainable Diets: Optimization

While scenario modeling is a common method for identifying sustainable diets, linear programming and optimization allow for harmonization of competing interests and the evaluation of tradeoffs. Numerous studies have used optimization to balance environmental, health, cost, and cultural components of diet (Gazan et al. 2018, van Dooren 2018, Wilson et al. 2019). Optimization can be used to design individual or population diets which meet specific requirements while minimizing or maximizing one or many of the sustainability dimensions. Most often, the relationship between the elements of dietary sustainability are explored after calculating the minimum cost or environmental impact of a nutritionally adequate diet (Gazan et al. 2018).

When optimization focused on nutrition and environmental outcomes, optimized diets contained more plant-based foods and less ruminant meat and dairy (Wilson et al. 2019). They also contained less sweets, refined grains, alcohol, and sugar sweetened beverages (Wilson et al. 2019). Research has not provided a consensus on the relationship between these diets and cost, as some studies show cost savings, while others are neutral (Wilson et al. 2019). Gephardt et al. (2016) used optimization to identify tradeoffs and synergies across the carbon, water, land, and nitrogen footprints of American diets and found the largest tradeoffs between carbon and water, and nitrogen and water. Additionally, they found that the most highly constrained diets had similar compositions and contained mainly seafood, vegetables, nuts, and starchy roots.

These methods are particularly well suited for research in schools because they provide concrete examples for application, and schools generally have established menus and nutrition standards. Additionally, changes to school lunch programs offer the opportunity for real-world implementation across large populations shaping their dietary preferences. Multiple studies have

used optimization to consider tradeoffs in water and carbon impacts and cost in European school lunches (Ribal et al. 2015, Benvenuti et al. 2016, Eustachio Colombo et al. 2019). These studies found that using optimization to define school lunch menus can reduce carbon emissions by 24 to 60% while maintaining costs.

Although there are many potential benefits to using optimization, this method is limited when the range of foods explored is small and when analyses lack measures of acceptability and the cultural components of diet (Gazan et al. 2018, van Dooren 2018, Wilson et al. 2019). Future optimization analyses should be considered in the context of food policy and include improved sustainability metrics on cultural acceptance, consumption, environmental impacts, and infectious disease risk and use of hormones in livestock.

Opportunity in School Lunch

In the U.S., the federal government can promote sustainable diets through the National School Lunch Program (NSLP). For over 70 years, the NSLP has been providing low-cost and free meals to students across the U.S. in public and non-profit private schools (FNS 2017). The U.S. Department of Agriculture's Food and Nutrition Service administers the program at the federal level and provides nutrition standards, technical assistance, and funding (CRS 2019). Funding is provided as reimbursements for meals served and USDA-purchased commodity foods called USDA Foods or entitlement foods. For a meal to receive reimbursement it must follow the nutrition standards and include three of the five required meal components (meat and meat alternative, fruit, vegetable, grain, and milk) with one of the components being a fruit or vegetable (PL 111-296, 2010).

In 2010, the Healthy Hunger Free Kid Act (HHFKA) updated the nutrition standards and introduced the community eligibility provision (CEP), and Farm to School program (PL 111-296, 2010). Under the CEP, school lunch is free for all students in districts where greater than 60% of students are identified as low-income (PL 111-296, 2010). About one in five schools (19%) offer free lunch to all students through this provision (USDA 2019). Farm to School is a grant and training program aimed at increasing local food procurement in schools and educating children on nutrition and food systems. As of 2019, 65% of schools report participating in Farm to School

programming such as serving food produced locally and offering taste tests, cooking demonstrations, and farm field trips (FNS 2021). Farm to School programming is aligned with the concept of sustainable diets as it improves student cooking and nutrition knowledge, promotes the consumption of nutritious foods, supports a strong local food economy, and builds communities between schools and farms (Christensen; et al. 2017, Prescott et al. 2020).

While the CEP reduces barriers to food access, and Farm to School aligns with concepts of sustainable diets, the overall sustainability of lunches offered through this program is not well understood (Forrestal et al. 2021). There are few studies which consider costs, nutrition and health outcomes, and cultural acceptance of foods in conjunction with environmental impacts of food production and waste management (Blondin et al. 2017, Blondin et al. 2020).

To date, the School Nutrition and Meal Cost Study (SNMCS) is the most comprehensive study of the nutritional adequacy, cost, and student satisfaction of school meals in the U.S. The SNMCS found that lunches provided through NSLP are more nutritious than lunches brought from home and that the HHFKA improved the overall nutritional quality of lunches (USDA 2019). However the average school food authority runs a financial deficit, suggesting that schools need more funding for meal programs (USDA 2019). A little over a third (36%) of students state that they “like” school lunch, but nearly 20% of calories from school lunch are wasted daily with higher rates for fruits and vegetables (USDA 2019). While the SNMCS assessed important indicators of sustainability (acceptability, cost, nutrient content, waste), it did not consider the environmental impacts associated with producing lunches or managing waste. Further, it does not consider the tradeoffs between these factors to guide recommendations for developing more sustainable lunch menus.

The few studies which have evaluated the environmental impacts of school food in the U.S. considered wasted milk at school breakfast and Meatless Monday programs (Blondin et al. 2017, Blondin et al. 2020). Meatless Monday options had lower carbon emissions (-74%) and water requirements (-51%) than previous menu items, but when benefits were averaged over the week there was no difference in overall impacts (Blondin et al. 2020). This suggests that offering meatless lunches one day a week is not sufficient to effectively reduce the environmental impacts

of the school lunch program. Another study considered how food served in the NSLP compared to the recommendations for the EAT-Lancet diet (Poole et al. 2020). This study found that lunches served in the NSLP contained more dairy, fruit, refined grains, red meat, and starchy vegetables than the EAT-Lancet targets.

Outside of the scientific literature, Friends of the Earth has produced two reports on the environmental impacts of school lunches served in California. The first report is a case study from the Oakland Unified School District (Kraus-Polk 2017). Over the course of two years, the district reduced the proportion of animal products on lunch menus by 30% and switch to “Mindful Meats” such as beef from dairy cattle. These menu changes decreased the carbon footprint, embedded water, and cost per lunch by 14% (0.70 to 0.61 kg CO₂ eq.), 6%, and 0.01 USD respectively. Additionally, they found that student satisfaction improved throughout the program. If other school districts adopted similar programs, this report suggests that emissions, water, and cost savings could be substantial.

The second report included the entire state and assessed the GHG emissions of menu items commonly served (Kraus-Polk and Hamerschlag 2021). In California’s largest districts, 94% of entrées contained animal proteins, with 25% including cheese and 16% including processed meats. While beef only represented 16% of total menu offerings, it accounted for nearly 60% of the total GHG emissions from lunches, and beef entrées were associated with 15 times more carbon emissions than vegetarian options. This suggests that changes to menus could be essential for lowering the environmental impacts of the NSLP. The feasibility of changing menus across the country is unclear, but findings from studies on student acceptance and consumption of meat alternatives in the U.S. have been positive (Eckart 2010, Lazor et al. 2010, Flores 2019).

Background and Significance

The global food system is driving climate change and environmental degradation while contributing to unprecedented levels of diet-related disease, and economic inequalities (Willett et al. 2019, FAO et al. 2020, Rockström et al. 2020). An essential step in resolving these issues is the widespread adoption of sustainable diets (Willett et al. 2019). Sustainable diets protect ecosystems, support human health and wellbeing, and are acceptable, accessible, economically fair, and affordable (FAO 2012, p.7). To encourage the widespread adoption of sustainable dietary patterns, sustainable diets must be well defined, studied, and promoted.

Governments have the power to support dietary change through federal food assistance programs. The U.S. National School Lunch Program (NSLP) offers an ideal setting to study and encourage sustainable dietary patterns as it serves a large population which is establishing habits for future consumption. Additionally, the program utilizes nutrition standards which already incorporate certain concepts of dietary sustainability.

Before the NSLP can encourage the consumption of sustainable diets, policy makers will need to determine the sustainability of lunches currently served and consider what changes need to be made to further improve sustainability. Information on lunch cost, nutritional quality, and student acceptance is available from the School Nutrition and Meal Cost Study which is the USDA's periodic assessment of the school meals programs (USDA 2019, USDA 2019, USDA 2019). However, there is little information on the environmental impacts of the lunches served or the relationship between meal cost, nutritional quality, environmental impacts, and student acceptance of school meals. To understand the potential for improvement, policy makers and school districts will need baseline estimates of sustainability indicators of lunches, such as global warming potential and water use. This information can then be used to develop recommendations for improvements which balance and consider the potential tradeoffs across indicators.

The **overall objectives** of this research were to evaluate the sustainability of school lunches served by the NSLP and create realistic alternative menus for schools using optimization modeling which balance tradeoffs across sustainability indicators to guide recommendations for

improvement. Sustainability was measured using lunch cost, student consumption and plate waste, nutritional quality, and environmental impacts global warming potential (GWP) (CO₂ eq), marine (N eq) and freshwater (P eq) eutrophication potential, land use (kg c deficit), and water consumption (m³) or water scarcity (m³ water eq.)¹.

Specific Aims

Aim 1: Estimate the environmental impact of a nationally representative sample of reimbursable lunches served through the NSLP. **Approach:** Using Life Cycle Assessment (LCA) and a nationally representative sample of over 2 million lunches served by the NSLP, this aim assessed the global warming potential (GWP) (kg CO₂ eq), marine (g N eq) and freshwater (g P eq) eutrophication potential, land use (m²a crop eq.), and water consumption (m³) of lunches served to kindergarten through twelfth grade students in the U.S. and explored the distribution of these impacts. This was accomplished by connecting life cycle inventories (LCIs) from the econinvent 3.6 database to foods served in the NSLP. Life Cycle Impact Assessment was performed in openLCA 1.10 using ReCiPe 2016 Midpoint methods. We explored the distribution of impacts across lunches and identified the contribution of impacts from quintiles and food groups. Finally, we examined the composition of lunches by quintile to focus policy recommendations.

Aim 2: Design weekly lunch menus for elementary students with minimal environmental impacts which meet the nutrition standards and cost constraints of the NSLP. **Approach:** Using integer linear programming this aim identified weekly lunch menus with the lowest global warming potential (GWP) (kg CO₂ eq.), land use (m²a crop eq.), water scarcity (m³ water eq.), and marine (g N eq.) and freshwater eutrophication (g P eq.) potentials while limiting food waste. This research quantified reductions in impacts by comparing optimized menus with baseline menus offered and reported on the relationships between the environmental impacts to explore tradeoffs and synergies. Data on menus offered during the 2018-2019 school year at Boston Public Schools were the basis for optimized menus. **Hypothesis:** Optimized weekly

¹ Over the course of this research data on water scarcity associated with U.S. food production became available. The first aim used data on water consumption, whereas the second and third aim use data on water scarcity.

menu will have lower environmental impacts than the weekly menus offered during the 2018-19 school year.

Aim 3: Design elementary school lunch menus with the greatest potential consumption rates and nutritional quality and lowest costs and environmental impacts and menus which harmonize these goals. **Approach:** Using integer linear programming, this aim identified weekly lunch menus with the greatest potential energy and value consumed, and nutritional quality measured using the Healthy Eating Index and lowest cost (USD), global warming potential (kg CO₂ eq.) and water scarcity (m³ water eq.). Using multi-objective functions, we identified menus which harmonized these goals. We then compared the modeled menus with current menus offered to make recommendations for improving school lunch menu planning. Data on menus offered during the 2018-2019 school year at Boston Public Schools were the basis for optimized menus. **Hypothesis:** Optimized weekly menus will have greater potential consumption rates and nutritional quality and lower costs and environmental impacts than the weekly menus offered during the 2018-19 school year.

References

The healthy, hunger-free kids act of 2010 (2010) PL 111-296

Aleksandrowicz, L., R. Green, E. Joy, et al. (2016). "The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: A systematic review." PLOS ONE **11**.

An, R. (2017). "Diet quality and physical activity in relation to childhood obesity." Int J Adolesc Med Health **29**(2).

Asghari, G., P. Mirmiran, E. Yuzbashian, et al. (2017). "A systematic review of diet quality indices in relation to obesity." British Journal of Nutrition **117**(8): 1055-1065.

Auestad, N. and I. I. I. V. L. Fulgoni (2015). "What current literature tells us about sustainable diets: Emerging research linking dietary patterns, environmental sustainability, and economics." Advances in Nutrition **6**(1): 19-36.

Bajželj, B., K. S. Richards, J. M. Allwood, et al. (2014). "Importance of food-demand management for climate mitigation." Nature Climate Change **4**(10): 924-929.

Bank, W. (2021). Employment in agriculture (% of total employment) (modeled ilo estimate). The World Bank online. Washington, D.C., World Bank.

Benvenuti, L., A. De Santis, F. Santesarti, et al. (2016). "An optimal plan for food consumption with minimal environmental impact: The case of school lunch menus." Journal of Cleaner Production **129**: 704-713.

Birney, C. I., K. F. Franklin, F. T. Davidson, et al. (2017). "An assessment of individual foodprints attributed to diets and food waste in the united states." Environmental Research Letters **12**(10): 105008.

Blackstone, N. T., N. H. El-Abbadi, M. S. McCabe, et al. (2018). "Linking sustainability to the healthy eating patterns of the dietary guidelines for americans: A modelling study." The Lancet Planetary Health **2**(8): e344-e352.

Blackstone, N. T., C. B. Norris, T. Robbins, et al. (2021). "Risk of forced labour embedded in the us fruit and vegetable supply." Nature Food **2**(9): 692-699.

Bleich, S. N., J. Segal, Y. Wu, et al. (2013). "Systematic review of community-based childhood obesity prevention studies." Pediatrics **132**(1): e201-210.

- Blondin, S. A., S. B. Cash, J. P. Goldberg, et al. (2017). "Nutritional, economic, and environmental costs of milk waste in a classroom school breakfast program." American journal of public health **107**(4): 590-592.
- Blondin, S. A., S. B. Cash, T. S. Griffin, et al. (2020). "Meatless monday national school meal program evaluation: Impact on nutrition, cost, and sustainability." Journal of Hunger & Environmental Nutrition: 1-13.
- Brunner, E. J., P. J. S. Jones, S. Friel, et al. (2008). "Fish, human health and marine ecosystem health: Policies in collision." International Journal of Epidemiology **38**(1): 93-100.
- Canning, P., S. Rehkamp, C. Hitaj, et al. (2020). Resource requirements of food demand in the united states. U. ERS, USDA ERS.
- Casas, R., S. Castro-Barquero, R. Estruch, et al. (2018). "Nutrition and cardiovascular health." International Journal of Molecular Sciences **19**(12).
- CDC (2019). "Childhood obesity facts | overweight & obesity | cdc."
- Chapa, J., B. Farkas, R. L. Bailey, et al. (2020). "Evaluation of environmental performance of dietary patterns in the united states considering food nutrition and satiety." Science of The Total Environment **722**: 137672.
- Christensen, L. O., B. B. R. Jablonski, L. Stephens, et al. (2017). Economic impacts of farm to school case studies and assessment tools, National Farm to School Network.
- Coleman-Jensen, A. (2019). Household food security in the united states in 2018. U. S. D. o. A. Economic Research Service, USDA: 47.
- Coleman-Jensen, A., Matthew P. Rabbitt, Christian A. Gregory, and Anita Singh (2020). Household food security in the united states in 2019. E. R. S. U.S. Department of Agriculture.
- Cote, A. T., K. C. Harris, C. Panagiotopoulos, et al. (2013). "Childhood obesity and cardiovascular dysfunction." J Am Coll Cardiol **62**(15): 1309-1319.
- Crippa, M., E. Solazzo, D. Guizzardi, et al. (2021). "Food systems are responsible for a third of global anthropogenic ghg emissions." Nature Food **2**(3): 198-209.
- CRS (2019). School meals programs and other usda child nutrition programs: A primer. C. R. Service, CRS Reports.

- Eckart, J. S., Kathryn A.; Moppert, Darlene K.; and Barnard, Neal D. (2010). "Students' willingness to purchase vegan menu items in the national school lunch program." Florida Public Health Review 7.
- EPA (2020). Inventory of u.S. Greenhouse gas emissions and sinks 1990-2018: ES-19-ES-21.
- Eustachio Colombo, P., E. Patterson, L. Schäfer Elinder, et al. (2019). "Optimizing school food supply: Integrating environmental, health, economic, and cultural dimensions of diet sustainability with linear programming." International journal of environmental research and public health 16(17): 3019.
- FAO (2012, p.7). Sustainable diets and biodiversity directions and solutions for policy, research and action. F. a. A. O. o. t. U. Nations. FAO Headquarters, Rome, Nutrition and Consumer Protection Division, FAO: p.7.
- FAO (2018). The state of world fisheries and aquaculture 2018 - meeting the sustainable development goals. Rome, UN FAO.
- FAO, IFAD, UNICEF, et al. (2020). The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. . Rome, FAO.
- FAO and WHO (2019). Sustainable health diets - guiding principles. Rome.
- Flores, R. E., Jill; Nash, Katie; Kwitowski, Edward (2019). "Implementation of vegan entrées in a washington, d.C. Elementary school." Journal of Child Nutrition & Management 43.
- FNS (2017). The national school lunch program. USDA. Washington, DC.
- FNS (2021). Research summary 2019 farm to school census report (summary). F. a. N. S. U.S. Department of Agriculture.
- Foley, J. A., R. DeFries, G. P. Asner, et al. (2005). "Global consequences of land use." Science 309(5734): 570-574.
- Forrestal, S., E. Potamites, J. Guthrie, et al. (2021). "Associations among food security, school meal participation, and students' diet quality in the first school nutrition and meal cost study." Nutrients 13(2).
- Gakidou, E., A. Afshin, A. A. Abajobir, et al. (2017). "Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990-2016: A systematic analysis for the global burden of disease study 2016." The Lancet 390(10100): 1345-1422.

- Garnett, T. (2014). "Three perspectives on sustainable food security: Efficiency, demand restraint, food system transformation. What role for life cycle assessment?" Journal of Cleaner Production **73**: 10-18.
- Gazan, R., C. M. C. Brouzes, F. Vieux, et al. (2018). "Mathematical optimization to explore tomorrow's sustainable diets: A narrative review." Advances in Nutrition **9**(5): 602-616.
- Gephart, J. A., K. F. Davis, K. A. Emery, et al. (2016). "The environmental cost of subsistence: Optimizing diets to minimize footprints." Science of The Total Environment **553**: 120-127.
- Global Panel (2016). The cost of malnutrition: Why policy action is urgent. London, UK, Global Panel on Agriculture and Food Systems for Nutrition.
- ILO (2009). FACTS ON Agriculture. Geneva, Switzerland, International Labour Organization.
- Han, J. C., D. A. Lawlor and S. Y. S. Kimm (2010). "Childhood obesity." The Lancet **375**(9727): 1737-1748.
- Heller, M. C., A. Willits-Smith, R. Meyer, et al. (2018). "Greenhouse gas emissions and energy use associated with production of individual self-selected us diets." Environ Res Lett **13**(4): 044004.
- HHS (2013). Managing overweight and obesity in adults systematic evidence review from the obesity expert panel, 2013. L. National Heart, and Blood Institute, National Institutes of Health, U.S. Department of Health and Human Services, U.S. Department of Health and Human Services.
- Hirvonen, K., Y. Bai, D. Headey, et al. (2020). "Affordability of the eat-lancet reference diet: A global analysis." Lancet Glob Health **8**(1): e59-e66.
- IPBES (2019). Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. J. S. E. S. Brondizio, S. Díaz, and H. T. Ngo. Bonn, Germany, IPBES secretariat.
- IPCC (2019). Summary for policymakers. In: Climate change and land: An ipcc special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. J. S. P.R. Shukla, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, IPCC.

- Jones, A. D., L. Hoey, J. Blesh, et al. (2016). "A systematic review of the measurement of sustainable diets." Advances in Nutrition 7(4): 641-664.
- Kennedy, E. and J. F. Guthrie (2016). "Nutrition assistance programs: Cause or solution to obesity." Current Obesity Reports 5(2): 176-183.
- Kirsten Jaglo, Shannon Kenny and J. Stephenson (2021). From farm to kitchen: The environmental impacts of u.S. Food waste. EPA. Washington, D.C., EPA.
- Kraus-Polk, J. and K. Hamerschlag (2021). The state of school lunch in california: Opportunities for improving the health and environmental profile of school food. Friends of the Earth.
- Kraus-Polk, K. H. a. J. (2017). Shrinking the carbon and water footprint of school food: A recipe for combating climate change, a pilot analysis of oakland unified school district's food programs. F. o. t. Earth.
- Land and Water Division FAO (2010). Water at a glance, the relationship between water, agriculture, food security and poverty. Rome, FAO.
- Lazor, K., N. Chapman and E. Levine (2010). "Soy goes to school: Acceptance of healthful, vegetarian options in maryland middle school lunches." J Sch Health 80(4): 200-206.
- Leung, C. W., E. S. Epel, L. D. Ritchie, et al. (2014). "Food insecurity is inversely associated with diet quality of lower-income adults." Journal of the Academy of Nutrition and Dietetics 114(12): 1943-1953.e1942.
- Lloyd, L. J., S. C. Langley-Evans and S. McMullen (2012). "Childhood obesity and risk of the adult metabolic syndrome: A systematic review." Int J Obes (Lond) 36(1): 1-11.
- Mackenzie, B., H. Mosegaard and A. Rosenberg (2009). "Impending collapse of bluefin tuna in the north east atlantic and mediterranean." Conservation Letters 2: 26-35.
- Micha, R., J. L. Peñalvo, F. Cudhea, et al. (2017). "Association between dietary factors and mortality from heart disease, stroke, and type 2 diabetes in the united states." JAMA 317(9): 912-924.
- Mohanan, S., H. Tapp, A. McWilliams, et al. (2014). "Obesity and asthma: Pathophysiology and implications for diagnosis and management in primary care." Exp Biol Med (Maywood) 239(11): 1531-1540.
- Moreno, L. A. and G. Rodríguez (2007). "Dietary risk factors for development of childhood obesity." Curr Opin Clin Nutr Metab Care 10(3): 336-341.

- Mozaffarian, D. and E. B. Rimm (2006). "Fish intake, contaminants, and human health: Evaluating the risks and the benefits." Jama **296**(15): 1885-1899.
- Nelson, M. E., M. W. Hamm, F. B. Hu, et al. (2016). "Alignment of healthy dietary patterns and environmental sustainability: A systematic review." Advances in Nutrition **7**(6): 1005-1025.
- Ornelas, I., W. Fung, S. Gabbard, et al. (2021). Findings from the national agricultural workers survey (naws) 2017–2018: A demographic and employment profile of united states farmworkers. J. International.
- OSCE (2009). A summary of challenges on addressing human trafficking for labour exploitation in the agricultural sector in the osce region Organization for Security and Co-operation in Europe.
- Park, M. H., C. Falconer, R. M. Viner, et al. (2012). "The impact of childhood obesity on morbidity and mortality in adulthood: A systematic review." Obesity Reviews **13**(11): 985-1000.
- Payne, C. L., P. Scarborough and L. Cobiac (2016). "Do low-carbon-emission diets lead to higher nutritional quality and positive health outcomes? A systematic review of the literature." Public Health Nutr **19**(14): 2654-2661.
- Perignon, M., F. Vieux, L. G. Soler, et al. (2017). "Improving diet sustainability through evolution of food choices: Review of epidemiological studies on the environmental impact of diets." Nutr Rev **75**(1): 2-17.
- Poirier, P., T. D. Giles, G. A. Bray, et al. (2006). "Obesity and cardiovascular disease: Pathophysiology, evaluation, and effect of weight loss." Circulation **113**(6): 898-918.
- Poole, M. K., A. A. Musicus and E. L. Kenney (2020). "Alignment of us school lunches with the eat-lancet healthy reference diet's standards for planetary health." Health Affairs **39**(12): 2144-2152.
- Prescott, M. P., R. Cleary, A. Bonanno, et al. (2020). "Farm to school activities and student outcomes: A systematic review." Advances in Nutrition **11**(2): 357-374.
- Rehkamp, S. and P. Canning (2018). "Measuring embodied blue water in american diets: An eio supply chain approach." Ecological Economics **147**(C): 179-188.
- Reinhardt, S. L., R. Boehm, N. T. Blackstone, et al. (2020). "Systematic review of dietary patterns and sustainability in the united states." Advances in Nutrition **11**(4): 1016-1031.

- Ribal, J., M. Fenollosa, P. García-Segovia, et al. (2015). "Designing healthy, climate friendly and affordable school lunches." The International Journal of Life Cycle Assessment **21**.
- Ridoutt, B. G., G. A. Hendrie and M. Noakes (2017). "Dietary strategies to reduce environmental impact: A critical review of the evidence base." Advances in Nutrition **8**(6): 933-946.
- Rockström, J., O. Edenhofer, J. Gaertner, et al. (2020). "Planet-proofing the global food system." Nature Food **1**(1): 3-5.
- Searchinger, T., R. Waite, C. Hanson, et al. (2019). World resources report, creating a sustainable food future, a menu of solutions to feed nearly 10 billion people by 2050. E. Matthew, WRI.
- Springmann, M., M. Clark, D. Mason-D'Croz, et al. (2018). "Options for keeping the food system within environmental limits." Nature **562**(7728): 519-525.
- Springmann, M., M. A. Clark, M. Rayner, et al. (2021). "The global and regional costs of healthy and sustainable dietary patterns: A modelling study." The Lancet Planetary Health **5**(11): e797-e807.
- Springmann, M., K. Wiebe, D. Mason-D'Croz, et al. (2018). "Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: A global modelling analysis with country-level detail." Lancet Planet Health **2**(10): e451-e461.
- Steffen, W., K. Richardson, J. Rockström, et al. (2015). "Planetary boundaries: Guiding human development on a changing planet." Science **347**(6223): 1259855.
- Tilman, D. and M. Clark (2014). "Global diets link environmental sustainability and human health." Nature **515**(7528): 518-522.
- Tilman, D., M. Clark, D. R. Williams, et al. (2017). "Future threats to biodiversity and pathways to their prevention." Nature **546**(7656): 73-81.
- USDA (2019). School nutrition and meal cost study: Volume 1 - school meal program operations and school nutrition environments (summary). J. Endahl. Alexandria, VA, Food and Nutrition Services **1**.
- USDA (2019). School nutrition and meal cost study: Volume 2 - nutritional characteristics of school meals. School Nutrition and Meal Cost Study. J. Endall, Food and Nutrition Services. **2**.
- USDA (2019). School nutrition and meal cost study: Volume 3 - school meal costs and revenues. School Nutrition and Meal Cost Study. J. Endall, Food and Nutrition Services. **2**.

- USDA (2019). School nutrition and meal cost study: Volume 4 - student participation, satisfaction, plate waste and dietary intakes. School Nutrition and Meal Cost Study. J. Endall, Food and Nutrition Services. **2**.
- van Dooren, C. (2018). "A review of the use of linear programming to optimize diets, nutritiously, economically and environmentally." Frontiers in Nutrition **5**: 48.
- WHO. (2020). "The top 10 causes of death." WHO's Global Health Estimates Retrieved December 27, 2021, from <https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death>.
- WHO (2021). Overweight and obesity. Retrieved December 27, 2021, from <https://apps.who.int/gho/data/view.main.BMI25CREGv?lang=en>
- Willett, W., J. Rockström, B. Loken, et al. (2019). "Food in the anthropocene: The eat–lancet commission on healthy diets from sustainable food systems." The Lancet **393**(10170): 447-492.
- Wilson, N., C. L. Cleghorn, L. J. Cobiac, et al. (2019). "Achieving healthy and sustainable diets: A review of the results of recent mathematical optimization studies." Adv Nutr **10**(Supplement_4): S389-s403.

Chapter 2 : Environmental impacts of the United States National School Lunch Program

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Abstract.

Altering dietary patterns is essential to ameliorating the environmental impacts of the world food system. The U.S. National School Lunch Program (NSLP) shapes the consumption of America's children and adolescents, providing a significant opportunity to reduce dietary environmental impacts. Here, we collate life cycle inventories relevant to the NSLP and assess the environmental impacts of a representative sample of lunches served in the U.S. during the 2014-2015 school year to inform school meal policy. The mean $\pm$ SE impact per lunch was 1.5 ± 0.03 kg CO₂ eq. climate change, 1.8 ± 0.03 m²a crop eq. land use, 0.055 ± 0.00 m³ water consumption, and 0.24 ± 0.05 g P eq. freshwater and 3.1 ± 0.00 g N eq. marine eutrophication. Meat products contributed the most (28-67%) to total impacts for all impact categories. Lunches in the top quintile of impacts contributed an outsized proportion to total impacts (~40%) suggesting that policy changes related to these lunches should be prioritized. To reduce the environmental impacts of the NSLP, our results support increasing whole grain requirements and providing serving size or frequency limits for beef.

1.0 Introduction

High income countries must shift their dietary patterns to address the increasing environmental burdens of food systems¹⁻³. Government programs and policies are important levers for shifting dietary patterns^{4,5}. Some countries are pursuing this shift by incorporating environmental sustainability into dietary guidelines⁶. However, there are numerous mechanisms for governments to influence national dietary patterns, including, but not limited to: consumer education, regulation of food products, taxation, and changes to standards and purchasing practices for government food programs.

In the United States (U.S.), the National School Lunch Program (NSLP) is a federally assisted meal program with multiple components including monetary support, surplus foods, and nutrition standards for school meals⁷. The program has an annual budget of 14 billion USD and in 2019, it provided lunch to nearly 40% of U.S. children daily⁸. With its considerable budget and reach, the NSLP is uniquely positioned to affect the dietary patterns of American children and adolescents and could aid in addressing the environmental impacts of food systems.

The NSLP is regularly assessed for cost and nutritional quality; however, the aggregate environmental impacts of producing the food for this program are not known^{9,10}. Baseline estimates of the environmental impacts of food served in the NSLP are needed to design menus and make policy recommendations which will reduce the environmental impacts of the program and help students develop preferences aligned with sustainable dietary patterns. Outside of the U.S., European school systems have begun to assess the environmental impacts of producing school lunch to inform school meal policy¹¹⁻¹⁷. These studies are culturally relevant to food consumed in European countries and primarily focus on global warming potential (GWP).

The environmental impacts of meal patterns recommended by the U.S. Dietary Guidelines for Americans and of adult diets in the U.S. are well documented¹⁸⁻²¹. These studies showed that diets lower in animal products produce fewer environmental impacts; however, these assessments are not specific to the meal composition or nutrition standards of large-scale national feeding programs or for children and adolescents. To understand the implications of

these programs, there is need for life cycle assessment (LCA) data tailored to American food programs that prioritize procurement from within the U.S. with impact results for multiple categories relevant to food systems (i.e., GWP, land use, water consumption, and eutrophication potential).

Accordingly, the objectives of this research were to: 1) collate life cycle inventories (LCIs) for foods served in the NSLP; 2) estimate the environmental impacts from the agricultural production of lunches; 3) explore the distribution of impacts across lunches and identify the contribution of impacts from quintiles and food groups; and 4) examine the composition of lunches by quintile to focus policy recommendations. We collated environmental impact data relevant to the NSLP and assessed the environmental impacts of a representative sample of lunches served (>2.2 million) in the NSLP during the 2014-2015 school year (SY).

2.0 Results

The School Nutrition and Meal Cost Study (SNMCS) collected data on over 2.2 million lunches served from a nationally representative sample of 1,207 schools and included over 1,300 unique food items. All lunches abided by the NSLP standards for a reimbursable meal which require students to select at least three items from the five offered meal components: milk, grain, fruit, vegetable, and meat/meat alternative, with one of the items being a fruit or vegetable. This allowed for a wide range of lunch composition with some lunches not including a meat/meat alternative or milk. Nearly all daily school lunch menus offered milk (>97%), a cooked vegetable (84%), and fresh fruit (72%), and almost half offered a starchy vegetable (46%), entrée salad (37%), sandwich with meat (36%), and pizza (31%). Examples of lunches served include whole wheat pasta with meat sauce, a whole wheat roll, tossed salad with creamy dressing, canned peaches, and 1% milk; fajita with chicken and vegetables, corn chips, and apple juice; beef patty, whole wheat roll, and mashed white potatoes; and peanut butter and jelly sandwich, apple, and carrots. More information on lunch offerings has been reported elsewhere⁹.

Linking environmental impacts of agricultural commodities to foods served allowed us to estimate the distribution of lunch impacts across schools and days. We report the mean

environmental impacts (global warming potential (GWP), land use, water consumption, freshwater eutrophication, marine eutrophication) of lunches served in the NSLP during the 2014-2015 SY per lunch as served, and standardized to 1000 kcal (Table 1). On average, lunches served contained about 620 kcal.

Quintile contributions to total impact and composition.

For each impact category, lunch impacts were divided into quintiles to consider the disproportionate contribution of certain lunches and explore trends in lunch composition. Cutoff values to assign lunches to quintiles were calculated using the 20th, 40th, 60th, and 80th percentile of each impact category. For example, the range of GWP across all lunches was 0.24 – 9.9 kg CO₂ eq. and the percentile cutoffs were as follows: 0.77, 0.99, 1.4, and 2.1 kg CO₂ eq. Lunches were assigned quintiles based on their impacts in relation to the cutoff values. A lunch with the GWP of 2.0 kg CO₂ eq. was in the 4th quintile. Each quintile (five for each impact category) represented ~440,000 lunches or 20% of lunches. For all impact categories, except water use and freshwater eutrophication, the lunches in the 5th quintile contributed to ~40% of total impacts (Figure 1). The impacts of each lunch generally did not fall within the same quintile for all impact categories. For example, a lunch containing a carton of milk, beef and cheese taco with extra cheddar cheese, pear, and corn with salsa was in the 5th quintile for GWP but 1st quintile for water consumption.

Lunch composition varied by quintile and impact category (SI Table 1). For the impact categories GWP, land use, and freshwater and marine eutrophication, lunches with the lowest impacts (in the 1st quintile) had more servings of fruit than lunches with the highest impacts (in the 5th quintile). Whereas, for water consumption, the opposite pattern emerged; lunches in the 5th quintile had greater servings of fruit compared to lunches in the 1st quintile. Compared to lunches in the 5th quintile, more servings of poultry and vegetables were observed in 1st quintile lunches for the impact categories GWP, land use, and marine eutrophication, but for water consumption and freshwater eutrophication, 5th quintile lunches had more servings of these food groups. While the impacts of a lunch generally fell within different quintiles across impact categories, the composition of lunches in the 5th quintile for the impact categories land use,

marine eutrophication, and the GWP were relatively consistent because these categories were strongly positively correlated ($r \geq 0.99$, $p < 0.05$).

Approximately 62,000 lunches were in the 1st quintile for *all* impact categories; hereafter, we refer to these as “low impact” lunches. Conversely, there were ~38,000 “high impact” lunches, which were in the 5th quintile for *all* impact categories. Before adjusting the results for energy, on average, low impact lunches were 50 kcal less than high impact lunches. All composition analyses controlled for differences in energy by adjusting impacts and composition using the average lunch energy content (620 kcal).

Low impact lunches were characterized by more servings of dairy, whole grains, seafood, and nuts and seeds (Table 2). These lunches contained more than twice as much cheese and seafood, ~1/3 oz. eq. more grain, and ~1/5 oz. eq. more nuts and seeds compared to high impact lunches. Units for meal component requirements (cup eq. and oz. eq.) are from the U.S. Dietary Guidelines for Americans and compensate for the different densities of foods²². Low impact lunches contained more dairy products, because cheese is a common substitute for meat in vegetarian lunches.

High impact lunches were characterized by more servings of fruit and fruit juice, meat (including beef, pork, and poultry), and vegetables. These lunches served 1 oz. eq. more meat and contained more than twice as much fruit juice, protein foods, and potatoes as low impact lunches.

Food group contributions to total impact.

Figure 2 shows the proportion of all lunches served by food group in grams and the percent contribution to total impact from each food group. Meat accounted for 8% of total lunch mass but contributed the most to all impact categories (28 – 67%). Within the meat category, beef accounted for a minor portion of mass (2%), but about half of all GWP, land use, and marine eutrophication potential. In our beef production model, GWP was driven by enteric fermentation, land use was driven by planted pasture, and marine eutrophication was caused by nitrate from fertilizer application and manure management.

After meat, dairy was the second largest contributor to all impact categories (17 – 29%) except water consumption (7%). Enteric fermentation was the major contributing factor to GWP from dairy, whereas feed production drove all other impact categories.

Meat (28%), fruit (27%), and vegetables (14%) had the greatest impacts on water consumption, which resulted primarily from irrigation. Poultry was particularly water intensive within the meat category accounting for 19% of water consumption. Of the water consumption attributable to chicken production, 73% was from irrigation of maize and other feed crops. Poultry contributed more to water consumption than beef because it is more commonly served in school meals and relies more on irrigated feed (per kg output). The most commonly served fruits and vegetables rely heavily on irrigation, including apples, oranges, orange juice, grapes, potatoes, tomatoes, carrots, and iceberg lettuce.

Nuts and seeds contributed <1% to all impact categories because of their low impacts compared to other commodities and lack of volume in school meals (0.2%). Nuts and seeds could therefore be an important focus for recommendations. However, we observed considerable variability in water consumption across nuts and seeds. For example, per kg, cashews and almonds required over 6 times more water than peanuts, sunflower seeds, and sesame seeds.

Proxy impacts.

We used 106 unique life cycle inventories (LCIs) from ecoinvent 3.6 to represent the 563 commodities in the Food Commodities Intake Database (FCID). Over half of all commodities required proxy assignments; meaning an LCI for a similar crop or group of crops was used because an exact match for a commodity was not available. Table 3 shows the percent of total impacts from proxies by food group and impact category. Compared to overall impacts, the contribution of impacts from proxies was minimal across impact categories (< 12%).

Uncertainty assessment.

By mass, the following commodities were the most commonly served in the NSLP: milk, apple, wheat, chicken, potato, tomato, beef, orange, carrot, and soybean oil. Rankings of commodity impacts were consistent across the methods used in this analysis and others (SI Table 2). Climate change, marine eutrophication, and land use rankings were the most consistent while water consumption was the least consistent.

3.0 Discussion

To our knowledge, this is the first study to assess the baseline environmental impacts of the U.S. NSLP. Previous research has explored the environmental impacts of school lunches in Europe, the average American diet, and the Dietary Guidelines for Americans^{11-21,23,24}. Differences in meal composition and methods for estimating impact can make comparisons across studies problematic, however the composition of low and high impact diets and contribution to impacts from food groups generally aligned across studies.

Previous research has shown that low impact diets have less animal products and more whole grains and legumes^{1,20,25}. Rose et al. (2019) found that American diets with low greenhouse gas emissions (GHGE) have about twice the whole grain, legume, and nuts and seed content and less than half the animal protein content of high GHGE diets. Low impact school lunches had similar differences with ~20% more whole grains, nearly 20 times more nuts and seeds, and four times less animal protein than high impact lunches. Differences in magnitudes across the studies can be explained by differences in the compositions of school lunch and the average American diet, modeling procedures, and coverage of impact categories.

Meat and dairy have repeatedly been identified as major contributors to dietary environmental impacts across impact categories, while fruits and vegetables have been linked to water use^{19-21,26}. The percent contribution of meat to lunch water consumption (28%) and GWP (67%) was similar to its contribution to impacts of the American diet (35% Blue Water and 55% GHGE)²¹. In school lunch, poultry stood out as a major contributor to water consumption (19%) because it is commonly served; poultry accounted for over half of all meat served in schools. This differed with poultry's contribution to water scarcity in the average American diet (5%), partially because

beef is consumed in relatively greater quantities in the American diet. Fruits and vegetables accounted for 40% of the water consumption of lunches. While this is a large proportion of impact, fruits and vegetables account for about 36% of lunch mass.

Shifting towards lower impact lunches.

The U.S. has ambitious goals for environmental protection which will require concerted efforts across government policy and programs and could include changes to nutrition standards for federal food assistance programs²⁷. Our estimates can be used to evaluate changes to standards and benchmark progress in reaching national environmental goals. Additionally, this work starts to identify potential areas for policy changes based on the composition of low and high impact lunches as well as the food groups which had the greatest contribution to impacts.

Any policy recommendations, however, must be considered in light of other components of dietary sustainability including food costs and access, school infrastructure, nutrition quality, and children's previous exposure to certain types of foods and acceptance of foods. While access to low impact foods could be an obstacle for certain districts, major food distributors and food service providers have made commitments to provide more environmentally sustainable menu options including more plant-based foods, which could make it easier for schools to begin serving more sustainable menus^{28,29}. As for student acceptance, food and nutrition education interventions can be paired with menu changes for effective implementation^{30,31}. Particularly, education related to food systems and the environmental impacts of agricultural and food waste have been successful^{32,33}.

Our work affirms the results of numerous studies which highlight beef as a major contributor to the environmental impacts of diets^{2,21,25,34}. We found that, on average, high impact lunches contained about 1 oz. eq. more beef than low impact lunches. In the context of the NSLP meal pattern requirements, this is the minimum daily serving of a meat or meat alternative for kindergarten through 8th grade lunches. Beef was also the single greatest contributor to GWP, land use, and marine eutrophication. Our findings suggest that to reduce the environmental impacts of school lunch, policy should consider limiting servings of beef.

Tens of thousands of lunches served during the 2014-2015 SY had low environmental impacts across impact categories, providing a wide array of examples to support recommendations. The composition of these lunches was generally consistent with previous work identifying low impact diets^{1,2}. One characteristic of these lunches was greater portions of whole grains, which partially compensated for lower servings of beef and pork. Federal policy could encourage service of low impact lunches by increasing the requirements for whole grains. Whole grains are a nutritious, low cost, diverse and versatile food group that might offer solutions to the tradeoffs commonly confronted when proposing the consumption of sustainable diets^{35,36}. We observed no difference in refined grain content of low and high impact lunches; therefore, an increase in the whole grain requirement would not be associated with changes to refined grains.

Low impact lunches also contained greater servings of seafood, and nuts and seeds. Within these categories, there is considerable variability in impacts across foods²⁶. To recommend serving requirements for these food groups, school districts would need further guidance specifying food types and production practices. In general, the impacts of nuts and seeds are relatively low compared to animal-based protein, however tree nuts such as almonds and pistachios require 3 to 6 times more water than animal proteins^{26,37}. Based on their environmental impacts, peanuts, the most served nut in school lunch, and less commonly served seeds such as sunflower, sesame, or pumpkin seeds could be good alternatives to tree nuts.

If federal policy set seafood requirements for lunch, fish should be sourced from well-managed, wild populations with fishing methods which reduce by-catch and habitat destruction³⁸. Fish produced in low-intensity, non-recirculating aquaculture could also be good options because they are associated with lower GWP than trawling fisheries³⁸. However, they have relatively high eutrophication potential and can threaten wild species genetics^{38,39}. In New England, school districts are sourcing Acadian Redfish (*Sebastes fasciatus*); because this species is sustainably managed and less commercially popular, it is also inexpensive⁴⁰.

If limits on the servings of beef are put in place, grains, nuts and seeds, and seafood might be strong potential replacements given their nutritional composition and potential to provide health

benefits^{35,41,42}. However, cost differentials might make this prohibitive in some circumstances, and new recipes incorporating these foods into entrées will be necessary. Additionally, it is important that any changes to standards be well received by students and school food administrators. Studies are needed to inform implementation (i.e., kid friendly recipes, logistics for cooking and sourcing) and limit unintended consequences such as increased food waste. Changes to school meals standards and practices should be incremental, flexible, and will take time.

Recommendations for fruit and dairy.

Dairy was found in greater quantities in the low impact lunches even though it was one of the leading contributors to all impact categories except water consumption. This was because low impact lunches on average contained more cheese. Cheese is classified as a meat or meat alternative for school meal planning⁴³. It is a common vegetarian option which is used as a substitute for beef or meat. The lowest impact lunches contained more cheese because cheese displaced meat. Cheese generally has greater environmental impacts than plant-based proteins or other meat alternatives. Additionally, because of potential issues with sodium and saturated fat content, increasing cheese in school lunch might not lead to the dual benefits of improved nutritional and environmental outcomes²⁶. Our results are therefore inconclusive regarding changes to recommendations for dairy.

The composition of the lowest and highest impact lunches were inconsistent across impact categories for fruit. As seen in our work and previous research, fruit is a major contributor to water consumption^{19,21,44}. Therefore, the lunches with the greatest water consumption had more servings of fruit than the lowest impact lunches in this category. This trend was not consistent across other impact categories. For all other impact categories, the lowest impact lunches had greater servings of fruit. This inconsistency presents a tradeoff between water consumption and the other impact categories, however on average the difference in amount of fruit between the highest and lowest impact lunches was trivial (~0.1 cup eq.). As with dairy, our results do not provide a conclusive recommendation for changes to fruit requirements.

Aligning the NSLP nutrition standards with conservation policy.

The NSLP is deeply tied to domestic agricultural markets through the Buy American Provision and United States Department of Agriculture (USDA) Foods program^{45,46}. An important function of the NSLP is to stabilize commodity prices by creating demand for goods. Given the relationship between the NSLP and U.S. agriculture, changing the school meals standards presents a unique opportunity to align the NSLP meal pattern requirements with USDA conservation efforts.

By shifting the NSLP recommendations, there is potential for school meals to create markets for products produced using conservation practices. Alley cropping and conservation crop rotations are two practices supported by USDA Environmental Quality Incentives Programs. These practices protect the environment by improving soil health and biodiversity, and improve farmers ability to respond to climate change. Integrating these practices can produce small grains, nuts, and seeds. If the NSLP standards required greater servings of these food groups, farmers could take advantage of the stable market prices provided by school districts and schools could potentially integrate products that were previously cost prohibitive (i.e., barley, oats, sunflower seeds). Linking recommendations to increase grains, nuts, and seeds in school lunch with these types of conservation practices could produce win-win-win cases for nutrition, environment, and economic outcomes. At the same time, political will is needed to make these connections reality. Unfortunately, as has been seen with slow progress in changing school meal standards and incorporating sustainability into the dietary guidelines, the outlook for this might not be strong.

Limitations and future directions.

This study used a nationally representative sample of foods served in the NSLP and consistent and transparent LCA data, however there were limitations in the data and methods. Due to data availability, we used water consumption as opposed to a water scarcity metric, the latter of which measures water use in relation to water availability. Estimates of water scarcity for the U.S. consumed foods are now available and could be integrated into future studies²¹. Most studies on the impacts of diets, including this work, end assessment at the farm or processor gate²⁰.

Although agriculture is the predominate driver of impacts, a full picture of impacts beyond the farm gate could be useful²⁶.

It should be noted that this study did not consider the proportion of beef in school lunches from dairy systems due to data limitations. Environmental impacts of beef from dairy production can be three times less than beef from beef breed animals²⁶. In 2018, 21% of beef consumed in the U.S. came from dairy systems⁴⁷. The NSLP receives surplus foods and might rely more on dairy beef than the national market. This would lower our estimated impact of lunches and impacts from meat and beef.

4.0 Conclusions

We identified the average environmental impacts of lunches served in the NSLP and explored the contribution of impacts from quintiles and food groups, and the composition of lunches. This study showed that the highest impact lunches produced disproportionate environmental impacts, with meat and dairy as the greatest contributors to most impact categories. However, dairy, a common vegetarian option, was also found in greater quantities in low impact lunches because it partially compensated for lower quantities of meat. Water consumption stood out across the impact categories because it was not only driven by meat, but also fruits and vegetables.

Our results suggest that limiting servings of beef and increasing servings of whole grains could be effective strategies for reducing the environmental impacts of the NSLP. These changes could be implemented through a wide range of mechanisms including policy and funding or program implementation. Due to the obstacles involved in updating nutrition standards, financial incentives and program implementation represent more near-term opportunities for improvement⁴⁸. Financial incentives, like those provided for procuring local food, could encourage districts to offer beef less frequently⁴⁹. Pairing financial incentives with food and nutrition education interventions such as gardening, cooking, food systems, and marketing campaigns, could further ensure that menu changes are well received, and alignment between student consumption and sustainable dietary patterns³⁰⁻³². Any changes however must be considered

jointly with other dimensions of sustainable diets, USDA agricultural policy, and studies which inform implementation.

5.0 Methods

School lunch data.

Information on the composition of lunches served in the NSLP was obtained from the School Nutrition and Meal Cost Study (SNMCS), the United States Department of Agriculture's (USDA) periodic assessment of the school meals program. The study addressed a wide range of research questions related to the U.S. school meals programs. Data collection methods for this study are reported elsewhere⁵⁰.

Data on school lunches served during the 2014-2015 school year were collected from a nationally representative sample of schools participating in the NSLP. Schools provided information on the types and quantities of foods served during a school week using a web-based survey. Each menu item was then linked to a 2011-2012 Food and Nutrient Database for Dietary Studies (FNDDS) code to uniquely identify foods and then align those data to a database containing their nutritional composition⁵¹.

Environmental data.

Data for calculating the environmental impacts of school lunches were obtained from the ecoinvent 3.6 database and one external study^{52,53}. Ecoinvent 3.6 contains well-documented LCIs for thousands of products produced around the world, including hundreds of agricultural commodities. Examples of LCIs for agricultural commodities in ecoinvent 3.6 include *apple production in the US* and *rice production in China*. This database does not contain LCIs for prepared foods or combination dishes, which are common in school lunches. To address this gap, we used recipes from the Food Commodities Intake Database (FCID) to translate commodity impacts to impacts of prepared foods and mixed dishes⁵⁴.

FCID contains a series of recipes which disaggregates foods commonly consumed in the U.S. into 563 unique agricultural commodities. The database contains over 7,000 recipes for the foods documented in the 2010-2011 dietary intake assessment portion of the U.S. National Health and Nutrition Examination Survey and is cataloged using FNDDS codes. Recipes provide the grams of agricultural commodities per 100 grams of a given food. For example, the food “Bacon cheeseburger, 1/4 lb meat, with tomato and/or catsup, on bun” is made up of 28 commodities including beef meat, wheat flour, cucumber, tomato puree, and milk. Our methods for translating impacts from commodities to foods closely follows the methods reported by Heller et al. (2018).

A hierarchical decision tree was used to select LCIs from ecoinvent 3.6 to represent all of the commodities in FCID (SI Figure 1). The decision tree allowed us to assess how LCI function, geography, and system boundaries best aligned with the FCID commodities. LCIs with U.S. geographical representation were prioritized because the NSLP has a provision to buy products produced in the U.S. when feasible. When LCIs with U.S. geographic representation did not exist, an LCI from a top importing country was used following USDA Foreign Agricultural Service Global Agricultural Trade System Data on U.S. food imports⁵⁵. In cases where there were no LCIs from the top importing countries, an LCI with global representation was used.

An LCI from a similar product or proxy group of LCIs was selected to represent the FCID commodity when an LCI was not available for a specific FCID commodity (SI Table 3). Similarity in LCI and FCID commodities were determined based on agricultural production practices, climate for production, and plant botany or animal physiology. For example, the LCI *tomato, fresh grade, open field production in Mexico* was selected to represent the FCID commodity *tomatillo*. For commodities that did not have an obvious connection to a single LCI, a proxy group was used. Proxy group assignment followed, where possible, the proxy groups developed by Heller et al. (2018).

To model the impacts of processing, such as milling or oil extraction, of FCID commodities, we modified existing LCIs. Specifically, LCIs for wheat flour, maize flour, rapeseed oil, and soybean oil were modified to quantify the impacts of the production of different oils and flours. Modifications included altering input energy sources and replacing the primary input products.

To alter input energy, global or regional energy inputs were replaced with U.S. energy mixes. For example, in the LCI *wheat grain dry milling to produce wheat flour in South Africa*, there is an input for low voltage electricity from a South African electricity grid mix. This was replaced with the same amount of low voltage electricity from a U.S. electricity grid mix. To replace primary input products, the primary agricultural commodity used in the milling process was replaced with a different product in the appropriate proportions. Wheat, maize, rapeseed, or soybean seeds were replaced in the LCIs to create LCIs for other flours and oils. For example, to determine the impacts from the FCID commodity barley flour, the input of wheat for the LCI *wheat grain dry milling to produce wheat flour* was removed and replaced with barley. All modified LCIs were considered proxies, and sensitivity analyses were performed to determine the impact from proxies. Besides these updates for oil extraction and milling, no other alterations to ecoinvent LCIs were made.

System boundaries of LCIs were from cradle to farm gate, except for flours and oils, which were to processor gate. All LCIs were developed in the past 20 years, based on average technology, and had a functional unit of 1 kg of commodity. More information on the modeling requirements for LCIs in ecoinvent 3.6 can be found elsewhere⁵².

Analysis.

Life cycle impact assessment (LCIA) results for agricultural commodities were calculated using ReCiPe 2016 Midpoint Hierarchical methods in openLCA 1.10.3⁵⁶. Results for all eighteen impact categories outlined in ReCiPe were determined; however, we only report on the five impact categories most pertinent to agricultural production: GWP, land use, water consumption, freshwater eutrophication potential, and marine eutrophication potential.

Quantities of foods reported in SNMCS were in their as-served form, therefore conversions were applied to agricultural commodity LCIA results to account for removal of inedible parts, standard food preparation, and cooking losses (SI Table 4). Conversion factors were derived from the Food Intakes Converted to Retail Commodities Database and other sources⁵⁷⁻⁵⁹. FCID recipes delineate if the commodities which make up each recipe are cooked or raw; therefore we

only applied cooking loss conversions to the cooked commodities in each recipe. For example, in a hamburger recipe, the beef would be converted from raw to cooked, but the lettuce would be raw and only a conversion for losses from inedible parts would be applied to the lettuce.

After conversions were applied, LCA results for FCID commodities were translated to prepared foods and mixed dishes using FCID recipes. SNMCS researchers had previously assigned each menu item an FNDDS code which aligns with FCID recipes. In cases where the FNDDS codes for SNMCS menu items were incorrect or did not align with FCID recipe foods because of differences in database versions, we connected menu items to FCID recipes by hand. To translate commodity impacts to impacts for prepared foods and mixed dishes, we multiplied the impact of a commodity by the proportion of the commodity in the recipe (SI Table 5). We then summed the weighted impacts across commodities for each food. This resulted in the impacts per 100 grams of each food, as served (SI Table 6).

The School Nutrition and Meal Cost Study (SNMCS) reported the total grams served of each menu item and the number of meals served. The average impacts of a lunch were calculated using survey design parameters provided by SNMCS. Impacts were estimated for lunches served regardless of potential food waste, any potentially wasted portion of food was included in these analyses. However, the additional impacts associated with the end-of-life stages for managing food waste such as emissions from landfilling and incineration were not included. To control for differences in lunch size when comparing impacts of lunches, we normalized lunch impacts and contents using the average energy (kcal) served. We then assessed the contribution of impacts from quintiles and food groups, and the composition of lunches in quintiles. We used two-sample *t* tests to detect differences in lunch composition of lunches exclusively in the 1st or 5th quintiles for all impact categories. All data analysis was performed in R studio 1.2.1335 in the R language version 4.0.3.

Uncertainty analyses.

To assess the robustness of the impact assessment methods and modeling tools, we compared our results for environmental impacts of agricultural commodities to impact results using different

impact assessment methods, software, and databases. Differences in impact assessment methods, software, and databases make direct comparisons of results difficult; therefore, we ranked impacts within the same methods and compared rankings using the standard deviation of rankings for each commodity and across impact categories. We looked at the ten most served commodities in the NSLP, which accounted for more than 65% of the total mass of food served.

Author contributions.

Conceptualization, all authors; methodology, A.S., N.T.B., and T.G.; data curation and analysis, A.S; Writing – original draft preparation, A.S.; review and editing, all authors; supervision, T.G.; all authors have read and agreed to the published version of the manuscript.

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Competing interest statement.

The authors declare no conflicts of interest.

Table 2-1. Environmental impacts of lunches served in the National School Lunch Program during the 2014-2015 SY.

	Mean (SE)				
	Global Warming Potential kg CO ₂ eq.	Land Use m ² a crop eq.	Water Consumption m ³	Eutrophication Potential	
				Marine g N eq.	Freshwater g P eq.
Per Lunch	1.5 (2.7E-2)	1.8 (3.4E-2)	5.5E-2 (6.6E-4)	3.1 (4.9E-2)	0.24 (1.6E-3)
Per 1000 kcal	2.4 (4.3E-2)	2.9 (5.5E-2)	8.9E-2 (1.1E-3)	5.0 (8.0E-2)	0.39 (2.7E-3)

SY = School year; SE = standard error of the mean is the variability of lunches from School Nutrition Meal Cost Study.

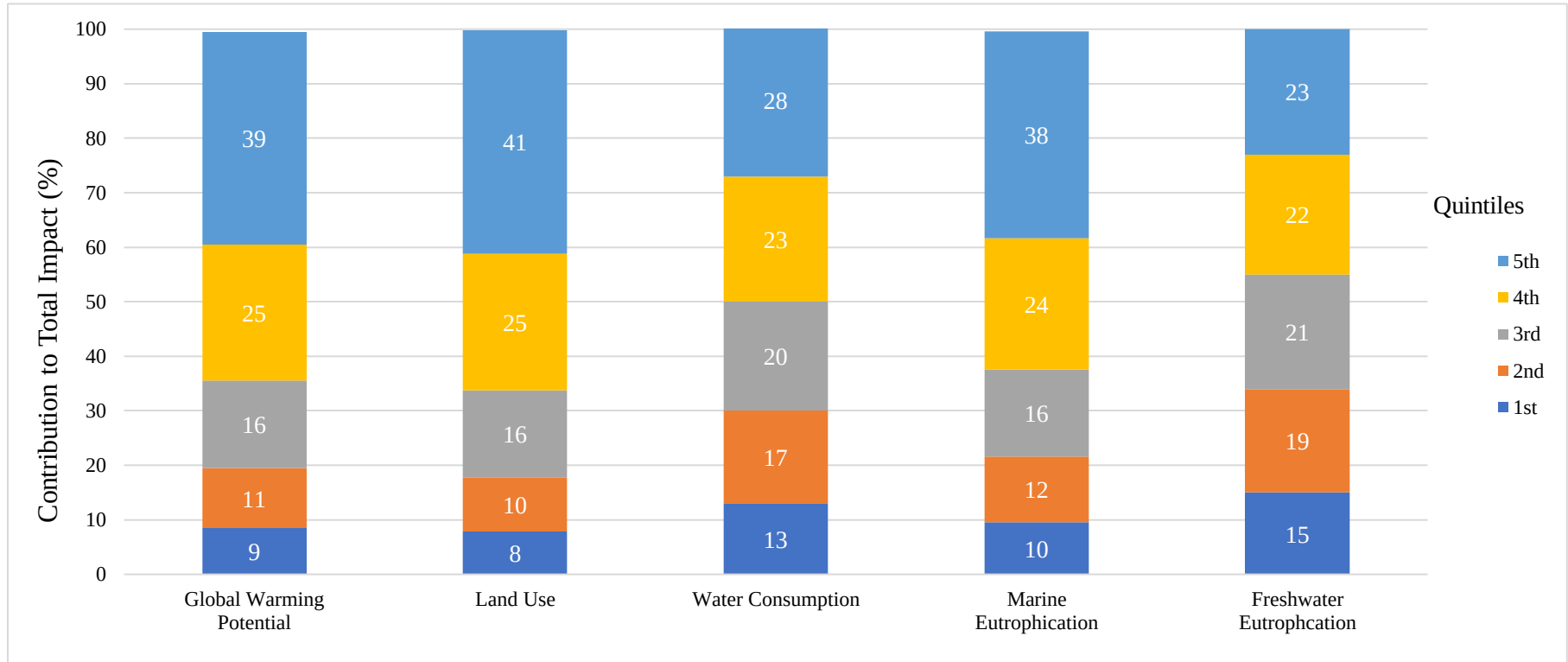


Figure 2-1. Percent contribution of quintiles to the total environmental impact of lunches served in the National School Lunch Program by impact category.

Lunch impacts for each impact category are divided into quintiles; each quintile represent 20% of lunches and is identified by a different color. Quintiles are stacked from 1st to 5th. Contribution of impacts from quintiles vary considerably across impact categories, with lunch impacts in the 4th and 5th quintile accounting for most of the total impact

Table 2-2. Average composition of lunches served by serving size in the National School Lunch Program exclusively in the 1st or 5th quintiles for all impact categories by food group.

Food Group	Low Impact Serving Size	High Impact Serving Size	p-value	
Fruit (cup eq.)	0.62	0.72	0.04	*
Fruit juices	0.05	0.17	0.00	****
Other fruit	0.57	0.55	0.03	*
Vegetables (cup eq.)	0.61	0.73	0.00	**
Red orange	0.23	0.19	0.07	
Starchy	0.11	0.20	0.00	****
Other fruit	0.13	0.17	0.05	
Beans and peas	0.05	0.05	0.89	
Dark green	0.10	0.12	0.24	
Protein foods (oz. eq.)	0.69	1.72	0.00	****
Beef and pork ¹	0.00	1.02	0.00	****
Poultry ¹	0.18	0.32	0.00	**
Cured luncheon meat ²	0.20	0.23	0.54	
Seafood	0.04	0.01	0.04	*
Eggs	0.01	0.03	0.00	**
Legumes	0.01	0.04	0.13	
Nuts and seeds	0.19	0.01	0.00	****
Soy products	0.04	0.04	0.82	
Dairy (cup eq.)	1.58	1.03	0.00	****
Cheese	0.71	0.26	0.00	****
Milk	0.86	0.76	0.00	****
Grains (oz. eq.)	2.42	2.12	0.00	****
Refined grains	0.98	0.96	0.79	
Whole grains	1.43	1.16	0.00	**
Oils (tsp)	1.60	1.66	0.55	
Added sugar (g)	4.29	3.35	0.00	****

Results are energy (kcal) adjusted averages of lunches exclusively in the 1st (low impact; n=62,000) or 5th (high impact, n=38,000) quintiles for all impact categories.

¹Excludes cured luncheon meat.

²Cured luncheon meat contains poultry, beef, and pork.

* <0.05

**<0.01

***<0.001

Food Groups	% Lunches by Mass	% Contribution to Total Environmental Impact				
		Global Warming Potential	Land Use	Water Consumption	Eutrophication	
					Marine	Freshwater
Fruits	20.0	1.3	2.1	26.5	1.7	3.2
Other fruit	15.0	0.8	1.3	16.5	1.1	2.0
Juice	5.0	0.5	0.8	10.0	0.6	1.2
Vegetables	16.0	2.8	2.5	14.3	3.2	8.4
Red orange	6.0	0.4	0.6	5.6	0.6	0.7
Starchy	4.0	0.7	0.8	6.1	1.1	4.1
Other	4.0	1.3	0.5	1.8	0.9	3.2
Beans and peas	1.0	0.2	0.6	0.5	0.3	0.3
Dark green	1.0	0.7	0.8	6.1	1.1	4.1
Meat	8.0	67.3	65.6	28.0	60.2	39.5
Poultry	5.0	9.5	6.1	19.2	9.3	18.4
Beef	2.0	52.5	56.0	4.6	47.3	13.6
Pork	1.0	5.2	3.5	4.2	3.6	7.5
Dairy	36.0	21.7	17.0	7.0	24.3	28.5
Grains	8.0	2.7	6.2	4.3	7.7	10.5
Other	5.0	1.8	2.4	4.2	1.0	1.4
Sweeteners	3.0	0.3	0.7	0.8	0.8	0.6
Oil	2.0	0.9	2.9	5.3	0.8	7.1
Egg	0.3	0.3	0.4	8.6	0.3	0.4
Seafood	0.2	0.9	0.0	0.4	0.0	0.2
Nuts and seeds	0.2	0.0	0.2	0.5	0.1	0.1

Table 2-3. Total lunch composition and percent contribution of impacts from food groups for lunches served in the National School Lunch Program.

Food group contribution to total impacts is a factor of commodity impacts from varying production practices and amount served. Mass of each food group is expressed as the percent of the total mass of all lunches served. Color ranges from light green and yellow to light and dark red to denote food groups' contribution intensity. Red cells represent the greatest contribution to lunch impacts, whereas light green represents the lowest contribution.

Table 2-4. Use of proxies in linkages to FCID and percent contribution of proxies to total impacts, by food group.

Food groups	# FCID commodities	% FCID commodities in group requiring proxies	% Total Impact from Proxies				
			Global Warming Potential	Land Use	Water Consumption	Eutrophication Potential	
						Marine	Freshwater
Fruit	153	56	0.3	0.3	2.7	0.3	0.5
Vegetables	189	63	0.6	0.9	2.1	0.9	2.0
Grain	44	48	1.4	0.9	2.8	1.3	2.7
Meat	58	40	0.0	0.0	0.1	0.0	0.0
Fish and seafood	6	33	0.0	0.0	0.1	0.0	0.0
Nuts and seeds	29	55	0.0	0.0	0.0	0.0	0.0
Eggs	6	0	0.0	0.0	0.0	0.0	0.0
Dairy	7	0	0.0	0.0	0.0	0.0	0.0
Oils and fats	26	62	0.3	0.5	3.1	0.3	1.0
Sweeteners	15	60	0.1	0.2	0.2	0.2	0.2
Other	29	45	0.0	0.0	0.5	0.0	0.1
Total diet	562	54	2.7	2.8	11.6	3.1	6.3

References

- 1 Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492, doi:[https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4) (2019).
- 2 Aleksandrowicz, L., Green, R., Joy, E., Smith, P. & Haines, A. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PLOS ONE* **11**, doi:10.1371/journal.pone.0165797 (2016).
- 3 Hallström, E., Carlsson-Kanyama, A. & Börjesson, P. Environmental impact of dietary change: a systematic review. *Journal of Cleaner Production* **91**, 1–11, doi:<https://doi.org/10.1016/j.jclepro.2014.12.008> (2015).
- 4 Afshin, A. *et al.* CVD Prevention Through Policy: a Review of Mass Media, Food/Menu Labeling, Taxation/Subsidies, Built Environment, School Procurement, Worksite Wellness, and Marketing Standards to Improve Diet. *Current Cardiology Reports* **17**, 98, doi:10.1007/s11886-015-0658-9 (2015).
- 5 Hyseni, L. *et al.* The effects of policy actions to improve population dietary patterns and prevent diet-related non-communicable diseases: scoping review. *Eur J Clin Nutr* **71**, 694–711, doi:10.1038/ejcn.2016.234 (2017).
- 6 Fischer, C. G. & Garnett, T. Plates, pyramids, planet Developments in national healthy and sustainable dietary guidelines: a state of plate assessment. (United Nations Food and Agriculture Organization, Food and Climate Research Network, 2016).
- 7 Vol. 116–94 (ed 79th Congress) (US Congress, Washington, D.C., 1946, amended 2019).
- 8 U.S. Department of Agriculture Economic Research Service. *National School Lunch Program*, <[https://www.ers.usda.gov/topics/food-nutrition-assistance/child-nutrition-programs/national-school-lunch-program.aspx#targetText=In%20fiscal%20year%20\(FY\)%202018,a%20cost%20of%20%2413.8%20billion.>](https://www.ers.usda.gov/topics/food-nutrition-assistance/child-nutrition-programs/national-school-lunch-program.aspx#targetText=In%20fiscal%20year%20(FY)%202018,a%20cost%20of%20%2413.8%20billion.>) (2019).
- 9 USDA. School Nutrition and Meal Cost Study: Volume 2 - Nutritional Characteristics of School Meals. (Food and Nutrition Services, 2019).
- 10 USDA. School Nutrition and Meal Cost Study: Volume 3 - School Meal Costs and Revenues. (Food and Nutrition Services, 2019).
- 11 De Laurentiis, V., Hunt, D. V. L. & Rogers, C. D. F. Contribution of school meals to climate change and water use in England. *Energy Procedia* **123**, 204–211, doi:<https://doi.org/10.1016/j.egypro.2017.07.241> (2017).

- 12 Martinez, S., Delgado, M. d. M., Marin, R. M. & Alvarez, S. Carbon footprint of school lunch menus adhering to the Spanish dietary guidelines. *Carbon Management* **11**, 427-439, doi:10.1080/17583004.2020.1796169 (2020).
- 13 Saarinen, M. *et al.* Life cycle assessment approach to the impact of home-made, ready-to-eat and school lunches on climate and eutrophication. *Journal of Cleaner Production* **28**, 177-186, doi:https://doi.org/10.1016/j.jclepro.2011.11.038 (2012).
- 14 Wickramasinghe, K. K., Rayner, M., Goldacre, M., Townsend, N. & Scarborough, P. Contribution of healthy and unhealthy primary school meals to greenhouse gas emissions in England: linking nutritional data and greenhouse gas emission data of diets. *Eur J Clin Nutr* **70**, 1162-1167, doi:10.1038/ejcn.2016.101 (2016).
- 15 Benvenuti, L., De Santis, A., Santesarti, F. & Tocca, L. An optimal plan for food consumption with minimal environmental impact: the case of school lunch menus. *Journal of Cleaner Production* **129**, 704-713, doi:https://doi.org/10.1016/j.jclepro.2016.03.051 (2016).
- 16 Eustachio Colombo, P. *et al.* Optimizing School Food Supply: Integrating Environmental, Health, Economic, and Cultural Dimensions of Diet Sustainability with Linear Programming. *Int J Environ Res Public Health* **16**, 3019, doi:10.3390/ijerph16173019 (2019).
- 17 Ribal, J. *et al.* Designing healthy, climate friendly and affordable school lunches. *The International Journal of Life Cycle Assessment* **21**, doi:10.1007/s11367-015-0905-8 (2015).
- 18 Heller, M. C., Willits-Smith, A., Meyer, R., Keoleian, G. A. & Rose, D. Greenhouse gas emissions and energy use associated with production of individual self-selected US diets. *Environmental research letters : ERL [Web site]* **13**, 044004, doi:10.1088/1748-9326/aab0ac (2018).
- 19 Blackstone, N. T., El-Abbadi, N. H., McCabe, M. S., Griffin, T. S. & Nelson, M. E. Linking sustainability to the healthy eating patterns of the Dietary Guidelines for Americans: a modelling study. *The Lancet Planetary Health* **2**, e344-e352, doi:10.1016/S2542-5196(18)30167-0 (2018).
- 20 Reinhardt, S. L. *et al.* Systematic Review of Dietary Patterns and Sustainability in the United States. *Advances in Nutrition* **11**, 1016-1031, doi:10.1093/advances/nmaa026 (2020).
- 21 Heller, M. C., Willits-Smith, A., Mahon, T., Keoleian, G. A. & Rose, D. Individual US diets show wide variation in water scarcity footprints. *Nature Food* **2**, 255-263, doi:10.1038/s43016-021-00256-2 (2021).
- 22 USDA and HHS. (ed U.S. Department of Agriculture and U.S. Department of Health and Human Services.) (Washington, D.C., 2020).

- 23 Chapa, J., Farkas, B., Bailey, R. L. & Huang, J.-Y. Evaluation of environmental performance of dietary patterns in the United States considering food nutrition and satiety. *Science of The Total Environment* **722**, 137672, doi:https://doi.org/10.1016/j.scitotenv.2020.137672 (2020).
- 24 Birney, C. I., Franklin, K. F., Davidson, F. T. & Webber, M. E. An assessment of individual foodprints attributed to diets and food waste in the United States. *Environmental Research Letters* **12**, 105008, doi:10.1088/1748-9326/aa8494 (2017).
- 25 Rose, D., Heller, M. C., Willits-Smith, A. M. & Meyer, R. J. Carbon footprint of self-selected US diets: nutritional, demographic, and behavioral correlates. *The American Journal of Clinical Nutrition* **109**, 526-534, doi:10.1093/ajcn/nqy327 (2019).
- 26 Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987, doi:10.1126/science.aag0216 (2018).
- 27 The White House. (Washington, DC, 2021).
- 28 (ed Sodexo press release) (Paris, FR, 2020).
- 29 Sysco. Sysco 2021 Corporate Social Responsibility Report. (2021).
- 30 Cohen, J. F. W. *et al.* Strategies to Improve School Meal Consumption: A Systematic Review. *Nutrients* **13**, doi:10.3390/nu13103520 (2021).
- 31 Kessler, H. S. Simple interventions to improve healthy eating behaviors in the school cafeteria. *Nutrition reviews* **74** **3**, 198-209 (2016).
- 32 Prescott, M. P. *et al.* Healthy Planet, Healthy Youth: A Food Systems Education and Promotion Intervention to Improve Adolescent Diet Quality and Reduce Food Waste. *Nutrients* **11**, doi:10.3390/nu11081869 (2019).
- 33 Jones, M. *et al.* Food sustainability education as a route to healthier eating: evaluation of a multi-component school programme in English primary schools. *Health Education Research* **27**, 448-458, doi:10.1093/her/cys016 (2012).
- 34 Peters, C. J. *et al.* Carrying capacity of U.S. agricultural land: Ten diet scenarios. *Elementa: Science of the Anthropocene* **4**, doi:10.12952/journal.elementa.000116 (2016).
- 35 McRae, M. P. Health Benefits of Dietary Whole Grains: An Umbrella Review of Meta-analyses. *J Chiropr Med* **16**, 10-18, doi:10.1016/j.jcm.2016.08.008 (2017).
- 36 Carlson, A., Lino, M. & Fungwe, T. The Low Cost, Moderate Cost, and Liberal Food Plans, 2007. (2007).
- 37 Mekonnen, M. M. & Hoekstra, A. Y. A Global Assessment of the Water Footprint of Farm Animal Products. *Ecosystems* **15**, 401-415, doi:10.1007/s10021-011-9517-8 (2012).

- 38 Clark, M. & Tilman, D. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters* **12**, 064016, doi:10.1088/1748-9326/aa6cd5 (2017).
- 39 Bohnes, F. A., Hauschild, M. Z., Schlundt, J. & Laurent, A. Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. *Reviews in Aquaculture* **11**, 1061-1079, doi:https://doi.org/10.1111/raq.12280 (2019).
- 40 Horwitz, S. *Sea to School: models of local, sustainable seafood for schools*, <<http://www.farmtoschool.org/news-and-articles/sea-to-school-models-of-local-sustainable-seafood-for-schools>> (2015).
- 41 Ros, E. Health benefits of nut consumption. *Nutrients* **2**, 652-682, doi:10.3390/nu2070652 (2010).
- 42 Hosomi, R., Yoshida, M. & Fukunaga, K. Seafood consumption and components for health. *Glob J Health Sci* **4**, 72-86, doi:10.5539/gjhs.v4n3p72 (2012).
- 43 USDA. Food Buying Guide for Child Nutrition Programs. (2020).
- 44 Tom, M. S., Fischbeck, P. S. & Hendrickson, C. T. Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. *Environment Systems and Decisions* **36**, 92-103, doi:10.1007/s10669-015-9577-y (2016).
- 45 FNS. Vol. 7 CFR 210.21 (d) (Food and Nutrition Services, United States Department of Agriculture 2017).
- 46 FNS. (ed USDA) (Food and Nutrition Services, United States Department of Agriculture, 2020).
- 47 Geiser, J. & Boetel, B. *Dairy cattle a big part of US beef supply*, <<https://www.farmanddairy.com/news/dairy-cattle-a-big-part-of-us-beef-supply/552832.html>> (2019).
- 48 Kogan, R. in *Health Affairs* (2019).
- 49 National Farm to School Network. State Farm to School Policy Handbook 2002-2020. (2021).
- 50 Zeidman, E. *et al.* School Nutrition and Meal Cost Study: Study Design, Sampling, and Data Collection. (U.S. Department of Agriculture, Food and nutrition Services, Office of Policy Support, Alexandria, VA, 2019).
- 51 USDA. in *Food Surveys Research Group* (U.S. Department of Agriculture, Agricultural Research Service, 2014).

- 52 Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., . The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment* **21**, 1218-1230 (2016).
- 53 Pelletier, N. Changes in the life cycle environmental footprint of egg production in Canada from 1962 to 2012. *Journal of Cleaner Production* **176**, 1144-1153, doi:<https://doi.org/10.1016/j.jclepro.2017.11.212> (2018).
- 54 EPA. (Office of Pesticide Programs University of Maryland, 2012).
- 55 (ed Foreign Agricultural Service U.S. Department of Agriculture, Global Agricultural Trade System) (2017).
- 56 European Commission. International Reference Life Cycle Data System handbook: framework and requirements for life cycle impact assessment models and indicators. (Luxembourg: Publications Officer, 2011).
- 57 Bowman S. A., M. C. L., Carlson J.L., Clemens J.C., Lin B-H., and Moshfegh A.J. (U.S. Department of Agriculture, Agricultural Research Service and U.S. Department of Agriculture, Economic Research Service, Beltsville, MD and Washington, D.C., 2013).
- 58 Weights, Measures, and Conversion Factors for Agricultural Commodities and Their Products. (Economic Research Service in cooperation with the Agricultural Marketing Service, the Agricultural Research Service and the National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C., 1992).
- 59 Heller, M. (ed University of Michigan Center for Sustainable Systems) (Ann Arbor, Michigan, 2019).

Chapter 3 : Designing school lunch menus with minimal environmental impacts using linear programming and optimization.

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Abstract.

In the United States, school lunch programs can decrease their environmental impacts by altering their menus. This modeling study used integer linear programming to provide a large urban school district with recommendations on designing lunch menus with reduced environmental impacts compared to baseline menus offered. On average, menus developed using optimization had environmental impacts (global warming potential, land use, water scarcity, marine eutrophication, and freshwater eutrophication) 54% lower than baseline menus while providing adequate variety, maintaining costs, and improving nutritional quality. Average reductions in impacts were smaller (27%) when models were subject to restrictions on the amount of theoretical weekly plate waste students create, however when waste constraints were applied, waste could be reduced by up to 23% compared to baseline. Minimizing any single environmental indicator reduced all impacts compared to the average impacts of baseline menus offered, suggesting synergy across the impact categories. However, when comparing impacts

across optimized weekly menus, we identified tradeoffs between water scarcity and other impact categories. Optimized menus offered a mix of poultry, vegetarian, and fish dishes each week and contained more vegetarian and fish options than baseline lunches offered. Our findings suggest that the school district should limit the frequency of beef entrées and replace these entrées with vegetarian and fish items while carefully considering seafood sourcing and student acceptance. The framework provided here for including environmental impacts in menu design could be translated across other school districts in the United States to enhance the environmental sustainability of the National School Lunch Program.

1.0 Introduction

There is an urgent need to address the environmental impacts of the world food system (Rockström et al., 2020). Dietary choice influences the magnitude of these impacts; as such, increasing the consumption of sustainable diets will be critical to addressing climate change, natural resource degradation, and the other mounting issues of the world food system such as malnutrition (Aleksandrowicz et al., 2016; Searchinger et al., 2019; Willett et al., 2019). By definition, sustainable diets safely and equitably provide adequate nutrition without compromising the wellbeing of earth's resources and ecosystems, society's cultural norms, and economic prosperity (FAO, 2012; Searchinger et al., 2019; Willett et al., 2019). As countries seek to promote changes in eating habits aligned with this concept, it is necessary to measure and manage tradeoffs that occur when striving to achieve these multiple and sometimes disparate outcomes (FAO and WHO, 2019).

Linear programming and other optimization methods are effective techniques for balancing competing goals and evaluating tradeoffs when studying diet sustainability. These methods are particularly well suited for research in schools because they can provide concrete examples for application, and schools generally have established menus and nutrition standards (2010). Additionally, changes to school lunch programs offer the opportunity for real-world implementation across large populations shaping their dietary preferences.

European studies of school lunch have used linear programming to consider tradeoffs in water and carbon impacts and cost but have not assessed tradeoffs across other environmental indicators (Benvenuti et al., 2016; Eustachio Colombo et al., 2019; Ribal et al., 2015). While the methods of these studies provide a strong basis for future analyses, the results are specific to each school district and country. A recent study established baseline estimates of the environmental impacts of the National School Lunch Program (NSLP) in the United States (U.S.) and provided recommendations for altering nutrition standards (Stern et al., 2022). This work identified possible tradeoffs in environmental impacts and called for clear guidance at the school district level for implementation studies. Providing school districts with clear examples of sustainable lunches and information on the tradeoffs that occur when planning menus is essential to effective implementation.

This research was conducted in collaboration with a large urban school district in the U.S. to identify weekly elementary school lunch menus with the lowest environmental impacts while meeting national nutritional requirements and district cost constraints. Integer linear programming and integer goal programming methods were used to; 1) identify the composition of weekly menus with the lowest global warming potential (GWP) (kg CO₂ eq.), land use (m²a crop eq.), water scarcity (m³ water eq.), and marine (g N eq.) and freshwater eutrophication (g P eq.) potentials while limiting food waste; 2) quantify reductions in impacts by comparing optimized menus with the baseline menus offered; and 3) report on the relationships between the environmental impacts to explore tradeoffs and synergies. This research provides a framework for U.S. school districts to reduce the environmental impacts of their meals along with example menus based on the case study district.

2.0 Methods

A week of lunch (five days) was chosen as the unit of analysis because the U.S. National School Lunch Program (NSLP) guidelines are based on weekly standards and school lunch programs typically follow three- to five-week menu cycles that repeat across the school year.

2.1 Data

2.1.1 Menu, nutrition, and cost

Boston Public Schools (BPS) serves approximately 53,000 students daily in 125 schools and provided information on foods offered to kindergarten to eighth grade students during the 2018-2019 school year. Daily lunches included the five required meal components (meat/meat alternative, grain, vegetable, fruit, and milk). Here we refer to the combination of meat/meat alternative and grains as an entrée.

Based on data availability and menu frequency, we included 142 menu items (>95% of menu items) from the 2018-2019 menus and purchasing records. Of these items, there were 77 entrées, 18 fruit sides, 43 vegetables sides, and four milk options (Table 1, SI Table 1). For each menu item, BPS provided data on the nutrient composition and cost per serving. School recipes

approved by the district's registered dietician were referenced when the information was provided for ingredients. For example, price and nutrition information were provided for shredded mozzarella and tortillas and a recipe for cheese quesadillas was used to quantify the cost and nutrient content of this entrée.

To limit the repetition of protein types and provide unique flavor profiles in optimized weekly lunch menus, we organized entrées into two subcategories. The first subcategory divided entrées by protein type: beef, chicken, fish, turkey, and vegetarian which included entrées with cheese (i.e., pizza, grilled cheese). The second subcategory was only used for some entrées and grouped foods by flavor profiles, cooking styles, and secondary protein types.

Table 1 lists select food options used in this analysis with their cost, calories, sodium, and saturated fat per serving and the baseline frequency of which they were served by menu item category (entrée, fruit, vegetable, and milk). The full list of food options is available in the supplement (SI Table 1).

2.1.2 Baseline menus offered

Data on the baseline menus offered during the 2018-2019 school year were used as a comparison for menus developed using optimization. We calculated the average baseline environmental impacts, cost, nutritional quality, and food waste of menus offered using the 2018-2019 school year menus and purchasing records.

2.1.3 Student plate waste

Empirical measurements of student plate waste for each menu item were collected to understand how waste would theoretically change if optimized menus were offered. Data on plate waste were captured from 7,000 lunches served across fifty days in twelve schools. This sampling method offered greater coverage of commonly served items. On average, there were about 270 observations per menu item; the number of observations per menu item ranged from 20 to 2,336. Foods with the most observations (>1000) included apples, 1% plain milk, cheese pizza, romaine lettuce, skim chocolate milk, and cucumber slices.

For some items served infrequently, little (< 20 observations) or no data on waste were collected. These foods remained in the optimization analyses because BPS has the capacity to prepare and serve them. We imputed data for missing or less frequent items by combining information on similar items (i.e., hamburgers and cheeseburgers) or using the 80th percentile of the proportion wasted for the respective menu item category or entrée subcategory. We used the 80th percentile because we expected waste rates for these foods to be higher than average. These items were unique (i.e., data on similar options were not available) and served infrequently ($\leq$ ten times per year); therefore, students would be less familiar with these items and likely to waste more. Of the 142 foods included in the analyses, we used the 80th percentile for twenty-one foods and combined data for fifty-seven foods (SI Table 2).

Standard techniques for quantifying student plate waste were used and are described elsewhere (Cohen et al., 2013). Briefly, we weighed each item served on a given day to capture a starting weight in grams. We then recorded what was served to each student after leaving the lunch line before consumption and collected trays when students were finished. Finally, we weighed each remaining item noting if an item was fully consumed based on what students were initially served. Waste information was reported in grams and only accounted for edible portions of foods (i.e., did not include banana peels, food packaging, etc.). We used average grams wasted per food item instead of a relative value, because regardless of the starting weight or type of food, the goal was to constrain the mass of waste produced.

2.1.4 Environmental impact data

Data for calculating the environmental impacts of lunches were obtained from the ecoinvent 3.6 database and two external studies (Heller et al., 2021; Pelletier, 2018). Ecoinvent 3.6 contains well-documented Life Cycle Inventories (LCIs) for hundreds of agricultural commodities. Additional information on environmental data including, LCI characteristics, selection process, connection of data to complex foods, conversions, and use of proxies is described elsewhere (Stern et al., 2022). Briefly, LCIs were selected from ecoinvent 3.6 to best represent agricultural commodities produced for a U.S. market. For most commodities, except minimally processed grains and oils, the system boundary was cradle to farm-gate. Life Cycle Impact Assessment was performed using ReCiPe 2016 Midpoint Hierarchical methods in openLCA 1.10.3. We

calculated impacts for each menu item for the following four impact categories pertinent to agricultural production: global warming potential (GWP), land use, freshwater eutrophication potential, and marine eutrophication potential.

As opposed to calculating water consumption using ReCiPe with ecoinvent, estimates for water scarcity were taken from the literature. Water scarcity is a more robust estimate of water impact compared to water consumption because it measures water use in relation to water availability. Additionally, literature values were specific to the U.S. Data on water scarcity were available for over 300 commodities commonly consumed in the U.S. from Heller et al. (2021). These values were estimated using blue water consumption from agricultural irrigation connected to geographic data on water scarcity and the AWARE100 method.

Environmental impacts were calculated for foods offered at baseline and on optimized menus. As such, the environmental impacts of the potentially wasted portion of food are included in these analyses. However, we did not include the additional impacts associated with the end-of-life stages for food waste such as transport, landfilling, compost, or incineration.

2.2 Linear Programming

Linear programming is used to find the best solution among many feasible solutions. It does this by selecting values for *decision variables* that maximize or minimize a linear *objective function* where the decision variables are subject to linear *constraints*. In this study, the decision variables were the number of servings of each menu item selected for a weekly menu. The objective functions aimed to minimize environmental impacts, and the constraints were the standards for the NSLP and cost requirements for the district. Linear programming is a unique case of constrained optimization in that the objective functions and constraints are linear. The standard form for linear programming is provided here:

$$\text{minimize } c_1x_1 + c_2x_2 + \cdots + c_nx_n$$

subject to constraints

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \geq b_1$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \geq b_2$$

⋮

$$a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n \geq b_m$$

and nonnegativity constraints

$$x_1 \geq 0, x_2 \geq 0, \dots, x_n \geq 0$$

Here we use two forms of linear programming, integer linear programming and integer goal programming. Throughout the paper we refer to these methods as optimization.

2.2.1 Objective functions

We used seven different objective functions (O1-O7) to identify and compare weekly menus which minimized individual and combined environmental impacts. This allowed us to explore tradeoffs across environmental indicators. All objective functions were linear.

The first five objective functions (O1-O5) minimized each individual environmental impact: (O1) global warming potential (GWP), (O2) land use, (O3) water scarcity, (O4) marine eutrophication potential, and (O5) freshwater eutrophication potential. The five objective functions were expressed mathematically by:

Equation O1-O5.

$$MIN f(impact) = \sum_{i=1}^{142} x_i * impact_i$$

where, $i = 1, \dots, 142$ represents the menu items, x_i is the decision variable and represents the number of servings of each i menu item selected, and $impact_i$ represent the environmental impact coefficients for GWP, land use, water scarcity, marine and freshwater eutrophication of each menu item. These objective functions separately estimated the minimum possible environmental impacts for a weekly menu for each impact category. The results of these functions were then used in the next objective function (O6) and are referred to as min_c where c represents each environmental impact category such that min_{GWP} is the minimum GWP; min_{land} is the minimum land use; min_{water} is the minimum water scarcity; min_{marine} is the minimum marine eutrophication; and min_{fresh} is the minimum freshwater eutrophication.

The next objective function (O6) used a method of integer goal programming described in Ribal et al. (2016) to minimize all impact categories simultaneously. Using the minimum environmental impacts for a weekly menu (min_c) determined using the first five objective functions, this function minimized the sum of the relative deviations from the minimum values. Specifically, we subtracted the impact of a weekly menu from the minimum impact and divided by the minimum impact. Each deviation was divided by the minimum impact to provide equal weighting and manage varying scales and units. Finally, we summed the relative, positive deviations across the selected menu items and calculated the minimum. The objective function was expressed mathematically by:

Equation O6.

$$MIN f(DEV) = \sum_{i=1}^{142} \sum_{c=1}^5 \left[\frac{(x_i * impact_{ic}) - min_c}{min_c} \right]$$

The final objective function (O7) used an alternate method for combining environmental impacts and can be compared with the goal programming methods used in O6. In the alternate method, we calculated a single composite environmental impact score (EIS) for each menu by summing the environmental impact values for each menu item across the impact categories.

To combine a menu item's impacts across impact categories (GWP, land use, water scarcity, marine and freshwater eutrophication) we first had to manage the different units and scales of each impact category. We did this by calculating the Z-score, which is a unitless number that describes the relationship between a food's impact and the mean impact across other foods. To calculate the Z-score, we first assessed the environmental impacts of over 7,000 foods commonly consumed in the U.S., then subtracted the impact of each food from the mean impact across all foods and divided by the standard deviation. For each menu item, we calculated five Z-scores, one for each of the five impact categories. The equation for the Z-score is provided here:

$$Z_c = \frac{t_c - \mu_c}{\sigma_c}$$

where Z_c is the Z-score for a menu item for each impact category, c represents the five impact categories, t_c is the impact value for a food for each impact category, and μ_c and σ_c are the mean impact and standard deviation across 7,000 foods for each impact category, respectively. Using this equation, some Z-scores were negative, and the lowest Z-score across all foods and impact categories was -0.86. To make all scores greater than or equal to one, we added a positive constant of 1.86 to all scores.

The five Z-scores for each food were then summed to calculate the EIS per food, as shown here:

$$EIS_i = \sum_{c=1}^5 Z_c$$

The EIS for each food ranged from 6 to 33, with 33 being the greatest possible impact for a food. The objective function minimized the sum of the EIS across menu items and was expressed mathematically by:

Equation O7.

$$MIN f(EIS) = \sum_{i=1}^{142} x_i * EIS_i$$

where, EIS_i represent the coefficients for the environmental impact score for each menu item.

2.2.2 Constraints

Constraints limit the possible combinations of decision variables selected. Decision variables were subject to constraints on nutrient content, meal pattern components, cost, food repetitions, and waste. Additionally, an integer constraint was applied to ensure that partial portions of foods were not selected. The school district has preestablished portion sizes for each menu item (i.e., it would be difficult for the school to serve half of a carton of milk). All model constraints were linear and are presented in Table 2.

The U.S. NSLP has standards for meal components and nutrients. Lunches are required to include certain amounts of fruit, vegetables, vegetable subgroups, grains, meats or meat alternatives, and fluid milk. Additionally, there are limits to calories, sodium, and saturated fat content. Units for meal component requirements (cup eq. and oz. eq.) are from the U.S. Dietary Guidelines for Americans and compensate for the different densities of foods (USDA and HHS, 2020).

Boston Public Schools has funds allocated for purchasing food for lunches and receives reimbursements from the federal government. Each lunch must be less than or equal to \$1.34, therefore a weekly menu must be less than or equal to \$6.70.

Variety in school meals is important for nutrition and student acceptance, therefore we included constraints on the number of times a food could be served within the week. Each weekly menu included exactly five servings of each meal component (entrée, fruit, vegetable, and milk). No entrée was repeated more than once throughout the week and no more than two foods from Subcategory 1 or one food from Subcategory 2 could be selected. This limited the model from choosing similar foods repeatedly. An exception for fish (Entrée Protein Type) was made; only one fish item could be selected each week because fish is not well liked by students (Kelly Thompson Nutrition Manager at Boston Public Schools, 2021). Each fruit and vegetable could be repeated up to two times per week and there was no constraint on repetitions of milk type.

The plate waste associated with baseline weekly menus offered ranged from 805 to 2,276 g, and on average was $1,291 \pm 288$ g. To ensure that optimized menus would not produce more than the average baseline waste, we incorporated waste constraints. Using baseline menu data we calculated the 10th, 15th, and 20th percentiles of weekly grams of food wasted and included these cutoff values as waste constraints in unique models when designing optimized menus.

2.2.3 Models

In total we ran seventeen distinct models which produced seventeen weekly lunch menus (Table 3). We did this to explore the differences between objective functions and to iteratively add constraints to the objective functions. The first seven models were performed using each

objective function (O1-O7) with the nutrition and cost constraints. We did not include repetition constraints in these models to understand which lunch items would appear more often if the repetition constraints were not applied. However, we included a total component constraint for entrées to ensure that five entrées were selected. We then ran seven models with each objective function (O1-O7), the nutrition and cost constraints, and the repetition constraints (+REP). Finally, our last three models used objective function O6 with the nutrition, cost, and repetition (+REP) constraints and additional constraints on waste at the 10th, 15th, or 20th percentiles (+W10, +W15, and +W20). All models produced menus which met the nutrition standards and meal pattern requirements for the NSLP, and the cost requirements for the district. Integer linear programming and integer goal programming were run in Microsoft Excel for Microsoft 365 MSO 16.0 in Solver with the Simplex algorithm. We compared results of each modeled menu to identify tradeoffs and synergies across the environmental indicators and certain foods or food groups.

3.0 Results

3.1 Environmental Impacts

3.1.1 Environmental impacts of optimized menus compared to baseline menus

Optimized weekly menus produced substantially lower environmental impacts than baseline menus offered during the 2018-2019 school year (Figure 1, SI Table 3). Regardless of objective function, minimizing any individual environmental indicator led to a reduction in all environmental impacts compared to the average impacts of baseline menus offered. For GWP, land use, and marine eutrophication potential, optimized menus had impacts at least 65% less than baseline menus offered (SI Table 3). For freshwater eutrophication and water scarcity, menus developed with optimization models had impacts up to 27% lower than average baseline menus offered.

3.1.2 Comparing environmental impacts across optimized menus

As expected, the lowest impacts were produced by the models without repetition constraints, and of those models, those which minimized a single environmental impact (MIN-GWP, MIN-

LAND, MIN-WATER, MIN-MARINE-EU, and MIN-FRESH-EU) produced the lowest impact across all models for that variable (SI Table 3). These impact values ($g = 1.7 \text{ kg CO}_2 \text{ eq.}$, $l = 2.0 \text{ m}^2 \text{ area crop eq.}$, $w = 0.7 \text{ m}^3 \text{ water eq.}$, $m = 4.3 \text{ g N eq.}$, $fw = 0.44 \text{ g P eq.}$) were subsequently used in the MIN-DEV model which minimized the sum of the relative deviations from the minimum for each environmental indicator. None of the models without repetition constraints consistently resulted in low impacts across impact categories. Specifically, the MIN-MARINE-EU and MIN-EIS produced the greatest GWP, land use, water scarcity, and freshwater eutrophication potential of the models without repetition constraints. The water scarcity impact of the MIN-MARINE-EU weekly menu was five times greater than the minimum water scarcity impact produced by the MIN-WATER weekly menu.

The minimum impacts of models with repetition constraints (+REP) were on average 68% greater than those without repetition constraints (SI Table 3). Across all models with repetition constraints, the MIN-DEV+REP and MIN-GWP+REP models produced the second lowest results for all impact categories. Apart from these models, all other models with repetition constraints produced water scarcity impacts more than 65% greater than the minimum water scarcity produced with the MIN-WATER+REP model.

3.1.3 Student plate waste

Environmental impacts of optimized and baseline menus included the cradle to farm or processor gate impacts of the whole menu regardless of potential waste; these analyses do not include additional impacts associated with end-of-life processing for waste.

When offered baseline menus, students wasted about 40% of food served by weight. Waste constrained models theoretically reduced waste by 18 to 23% from the baseline which is equivalent to two slices of cheese pizza each week (Figure 2). Waste constrained models also reduce average environmental impacts of baseline menus 27%. However, the environmental impacts of these models were on average 92% greater than the MIN-DEV+REP impacts (SI Table 3).

Without waste constraints, on average, optimized menus with repetition constraints theoretically produce about 58 more grams of waste weekly or about half a serving of a hot dog on a bun with popcorn compared to baseline menus offered. This suggests that lower environmental impact foods were associated with greater waste and was confirmed by negative correlations between food impacts and proportion

3.2 Weekly Menu Composition

Optimized weekly menus were smaller in mass, had fewer calories, saturated fat, and sodium, and more fiber than baseline menus offered during the 2018-2019 school year (SI Table 4). On average, weekly baseline menus had 15 more grams of saturated fat and 253 kcal more energy than optimized menus. While some optimized menus had lower fiber content than baseline menus, on average, optimized menus included 5 more grams of fiber per week.

Figure 3 shows the proportion of entrée protein types in optimized menus and baseline menus offered during the 2018-2019 school year. Boston Public School baseline entrée offerings were divided across chicken (28%), beef (29%), and vegetarian (35%), with fewer offerings (<8%) of turkey and fish. This contrasted with the optimized menus which in most cases did not include beef and had greater proportions of fish (10-30%), and vegetarian options (50-70%). For all optimized menus, 20% of entrées contained poultry.

The most selected entrées for the optimization models were cheese bites, hummus with vegetables, cheese, and flatbread, tuna with pita bread, garden salad and tuna, and crispy chicken sandwich (Figure 4). Nearly all menus developed with the repetition constraint models included these entrées and curry or teriyaki chicken (Table 4, SI Table 5). Compared to menus offered during the 2018-2019 school year, cheese bites and hummus with vegetables, cheese, and flatbread were up to 17 times more prevalent in optimized menus and hamburgers, spaghetti with meatballs, and pizza were not selected unless waste constraints were applied. The most selected fruits and vegetables were bananas, fresh; watermelon, fresh; raisins; blueberries, frozen; sweet potato wedges; romaine, raw; side salad, kale and apple; beans, sizzilin' black beans (a hot bean salad seasoned with cumin, chili powder, salsa, peppers, and onions); and Mexican street style corn (SI Figure 1, SI Figure 2).

Nearly all optimized menus, regardless of objective function, had lower environmental impacts for all impact categories than baseline menus (SI Table 3). This suggests some degree of synergy among the environmental indicators across models. Among the models with repetition constraints, the MIN-DEV+REP model had the greatest average reduction (-59%) in all environmental impacts compared to baseline menus offered, followed by the MIN-GWP+REP (-58%) and the MIN-WATER+REP (-57%) models.

3.3 Synergies and Tradeoffs

We observed tradeoffs between most impact categories and water scarcity for the repetition constrained menus. This means that when the objective function did not minimize water scarcity, water scarcity impacts were well above the minimum. The menu produced with the MIN-LAND+REP model had water scarcity impacts 76% greater than the minimum, and the MIN-EIS+REP and MIN-MARINE-EU+REP menus had water scarcity impacts more than 100% greater than the minimum (Figure 1; SI Table 3). The MIN-DEV+REP model, which produced the greatest average reduction in all environmental impacts compared to baseline, had the lowest tradeoffs across indicators. The environmental impacts of the MIN-DEV+REP menu were on average 6% greater than the minimum for all impact categories.

To identify entrées which promoted synergy, we looked across the models which minimized an individual environmental impact, with and without repetition constraints, and identified items that were selected by at least four models with different environmental goals. For example, hummus with vegetables, cheese, and flatbread was selected by GWP, LAND, WATER, FRESH-EU, and MARINE-EU models (SI Table 5). The other menu items identified were cheese bites, garden salad with tuna, and tuna with pita bread. The cheese bites entrée was effective for reducing all environmental impacts, while the tuna entrées were effective at reducing all impacts except for water scarcity and global warming potential.

4.0 Discussion

4.1 Lunch Impacts in Context

This research used real world data to define lunch menus with reduced environmental impacts compared to baseline menus offered. We found that using optimization to define lunch menus can substantially reduce the environmental impacts of school lunches while improving nutritional quality, and meeting nutrition and cost requirements. Optimized weekly menus contained more vegetarian and fish options than lunches offered, and synergy was observed across all environmental impacts except for water scarcity.

Previous research supports these findings; in studies of European schools, researchers found that using optimization to define school lunch menus can reduce carbon emissions by 24 to 60% while maintaining costs (Benvenuti et al., 2016; Eustachio Colombo et al., 2020; Eustachio Colombo et al., 2019; Ribal et al., 2015). While the recipes used in European schools were different than those used in the U.S., similarities in composition of optimized menus emerged. All optimized menus were omnivorous, meaning that they included both plant and animal products including poultry and dairy. Optimized menus generally reduced red meat and included multiple servings of fish, grains, and legumes. By contrast, the menus developed for European schools included small amounts of beef, pork, or eggs, whereas the models in this study generally eliminated all red meat and from the outset, did not include pork or egg options.

We observed tradeoffs between most indicators and water scarcity and consistency in the composition of menus across models with repetition constraints. Similar results were noted by Gephart et al. (2016); that study used optimization to identify tradeoffs and synergies across carbon, water, land, and nitrogen footprints of American diets and found the largest tradeoffs between carbon and water, and nitrogen and water. Additionally, they found that the most highly constrained diets had similar compositions containing mainly seafood, vegetables, nuts, and starchy roots.

4.2 Altering future menus

The average environmental impacts of baseline lunches offered were far greater than optimized menus partially because of beef. Numerous studies have identified beef as a major driver of dietary environmental impacts and 29% of entrées offered at baseline contained beef (Aleksandrowicz et al., 2016; Heller et al., 2018; Poore and Nemecek, 2018; Rose et al., 2019).

Despite their low costs, our models only selected beef entrées when waste constraints were applied. To provide students with lunches with minimal environmental impacts, beef entrées should be served less frequently. In this study, beef options were displaced by vegetarian and fish options, and poultry offerings were slightly reduced.

The optimization models chose vegetarian options at least 50% of the time and the most highly selected entrées were vegetarian (cheese bites and hummus). This generally aligned with BPS current practices as more than a third of all entrées offered during the 2018-2019 school year were vegetarian. While BPS is seemingly already providing enough vegetarian options to reduce environmental impacts, the school district does not highlight these menu items and in almost all circumstances, the vegetarian option is provided as an alternative to a meat option. In some schools, BPS offers a vegetarian option each day, but in schools without this standard, a peanut butter and jelly sandwich or grab and go vegetarian option is made available to children. The peanut butter and jelly sandwich or grab and go options are not formally listed on the menu, and it is uncommon (<10% of students) for students to select these items (Kelly Thompson Nutrition Manager at Boston Public Schools, 2021). To successfully reduce the environmental impacts of menus, BPS should make vegetarian options the focal point of the menu or the primary entrée offered and increase the frequency of these options. Similar to our findings, previous research on meatless Mondays suggests that changing menus one day a week is not sufficient to reduce dietary impacts (Blondin et al., 2020). Therefore, vegetarian options should be offered as the main entrée two days a week.

Major differences in the frequency of fish entrées were observed between baseline menus offered (5%) and optimized menus (10-30%). Fish entrées were selected across all objective functions but were most frequent for the LAND, MARINE-EU, and FRESH-EU models. This was because the fish selected was wild caught which does not require feed production like farmed fish. This finding is confirmed by a recent study on the environmental impacts of seafood, which found that greenhouse gas emissions is the major impact of concern for wild caught seafood, whereas land use and eutrophication potential are minimal (Gephart et al., 2021). Current LCA techniques do not have impact categories for overfishing or other impacts relevant to fisheries management. Garden salad with tuna was one of the most selected entrées and was even selected in waste

constrained models. However, acceptance of this food is uncertain because the waste for this item was estimated using data from other entrée salads. Collecting waste data on this item was difficult because it was only served five times throughout the 2018-2019 school year. Incorporating more fish entrées, could be an effective means for BPS to reduce the environmental impacts of menus, however they must be thoughtful regarding the sourcing (farmed versus wild) and student acceptance.

One caveat to increasing fish and vegetarian entrées is student acceptance and food waste. We showed here, with the MIN-DEV+REP+W20 model that compared to lunches offered, food waste can be lowered while still reducing the environmental impacts associated with food production. However, we still suggest that BPS develop and test new recipes and create marketing campaigns to promote and gain student acceptance for vegetarian and fish entrées, as plate waste is an imperfect measure of acceptance. Additionally, student acceptance is a function of acculturation over time, and introducing lower impact foods to children at younger ages might be effective.

4.3 Methods for simultaneous reduction of impacts

We tested two methods to simultaneously reduce environmental impacts of school lunch menus. Minimizing the sum of the relative deviations (DEV) was more successful at reducing impacts across indicators than minimizing a combined Environmental Impact Score (EIS). The combined impact score (EIS) was potentially less successful because of scaling issues. Specifically, the range of water scarcity Z-scores was greater than all other impact categories. This is relevant because the EIS models had the greatest issue minimizing water scarcity, and in the repetition restricted model produced similar water scarcity impacts to the average impact of lunches offered. The range of water scarcity Z-scores is inherent to the wide range of water impacts across agriculture, but future research could consider additional transformations to further align the distributions of Z-scores with the other impact categories. It should be noted, however, that in some cases the EIS method was more effective than minimizing a single environmental indicator. Additionally, the EIS method required fewer resources and time, as the DEV method required the collection of data from models before it could be implemented.

4.4 Limitations and future directions

This research had limitations which might hinder its effective translation. While our study used plate waste data from over 7,000 student lunches, many foods still lacked adequate data coverage. The choice to include items with limited data allowed for a wider breadth in menu items but diminished the certainty of waste estimates. We felt that it was more important to have greater menu item coverage than waste data certainty because it provides BPS with more information on potential menu changes. The repeated selection of tuna with pita bread, which was only offered once during the 2018-2019 school year, is testament to the importance of keeping less frequent items within the analyses. Additionally, waste data could easily be impacted by numerous factors such as marketing and promotion, the time students start lunch, having lunch after recess, allowing for a longer lunch period, and changing the cafeteria environment (Metcalf et al., 2020; USDA, 2019). Ultimately, by including more menu options this analysis allowed for a richer exploration of menu differentiation for BPS as they plan their menus. Future studies might consider different plate waste metrics including average waste of lunches instead of each menu item, because the combinations of menu items might impact waste generation.

Compared to menus offered, optimized menus selected a greater proportion of fish entrées. This was partially explained by the low eutrophication and land impacts associated with wild caught fish. Other impact categories related to fisheries management such as by-catch and biodiversity might be more relevant and should be included in future analyses if BPS is to include more wild caught fish on menus.

This research did not include the environmental impacts of foods beyond the farm gate. This research considered the potential amount of waste generated by optimized menus but did not include the environmental impacts associated with processing waste. Although the environmental impacts of agriculture account for most dietary impacts, full LCA data covering cooking, refrigeration, and waste management could provide a clearer picture of the absolute impacts of school lunch programs.

These analyses provided information for one week of lunches. Future analyses could consider longer time spans and the potential for multiple options per meal component each day. Additionally, research is needed to test the ease of implementation and acceptance of optimized menus in schools as has been performed in Swedish school districts (Eustachio Colombo et al., 2020).

School food programs in the U.S. use software to help nutrition managers design menus which meet the NSLP requirements. If school districts were to connect environmental impact data on menu items, as we did here, they could incorporate environmental impact limits or constraints on their menu planning. This could allow other school districts as well as other public meal programs such as the Child Adult Care Feeding Program and meals for pre-school age children to incorporate environmental impacts into menu planning.

5.0 Conclusions

This research used optimization methods to support a large urban school district in defining lunch menus with reduced environmental impacts compared to baseline menus offered. Overall, optimization was an effective strategy for designing menus with lower environmental impacts compared to the baseline menus offered, and integer goal programming techniques allowed for minimization of multiple impacts simultaneously. Additionally, optimized menus met nutrition, cost, and variety requirements. However, without waste constraints, on average, optimized menus produced more waste than baseline menus which suggests that students might not prefer the foods commonly selected for optimized menus. Therefore, to lower the impacts of lunch menus the school district could commit resources to gaining student acceptance of less frequently served items with lower environmental impacts and begin to replace beef with fish and vegetarian offerings.

Table 3-1. Cost, nutrient content, and frequency of select menu items offered during the 2018-2019 school year for designing weekly lunch menus with minimal environmental impacts.¹

Menu Item Category	Entrée Primary Protein Type	Entrée Flavor Profile ²	Menu Item Name ³	Cost (USD)	Energy (kcal)	Sodium (mg)	Sat. Fat (g)	Frequency Offered ⁴ (%)
Entrée	Beef	Tomato Salsa	Beef Burrito	0.74	455	610	9.50	1.4
Entrée	Beef	Tomato Salsa	Beef Taco	0.56	435	480	11.00	2.0
Entrée	Beef		Cheeseburger	0.34	301	594	4.50	4.3
Entrée	Beef	Cheese	Meatball Pizza	0.74	305	782	5.00	1.3
Entrée	Chicken	Barbecue	BBQ Chicken Drumstick with Brown Rice	0.92	300	675	2.15	0.4
Entrée	Chicken	Barbecue	BBQ Chicken Drumstick with Cornbread	1.28	370	765	2.65	0.9
Entrée	Chicken	Cheese	BBQ Chicken Pizza	0.74	300	786	4.75	2.4
Entrée	Chicken	Salad	Buffalo Chicken Garden Salad	0.82	231	485	3.75	1.5
Entrée	Chicken	Soy/Orange	Teriyaki Chicken with Lo Mein Noodles	0.64	245	590	3.00	1.5
Entrée	Chicken	Soy/Orange	Teriyaki Chicken with Vegetable Fried Rice	0.76	399	504	1.00	1.8
Entrée	Fish		Baked Fish and Cornbread	1.32	410	560	2.50	0.0
Entrée	Fish		Baked Fish Sandwich	1.07	441	829	3.00	1.6
Entrée	Fish	Tomato Salsa	Fish Taco	0.94	505	550	8.50	0.6
Entrée	Fish	Salad	Garden Salad and Tuna	0.55	147	280	0.98	0.6
Entrée	Turkey	Salad	Chef Salad with Turkey and Cheese and Pita	1.04	346	850	3.25	2.0
Entrée	Turkey		Roast Turkey with Cornbread and Gravy	1.12	277	812	1.34	0.6
Entrée	Turkey		Turkey and Cheese Sandwich	1.14	267	841	1.50	0.6
Entrée	Vegetarian	Tomato Salsa	Bean Burrito	0.66	459	1048	6.10	3.3
Entrée	Vegetarian	Tomato Salsa	Bean Taco	0.48	439	918	7.60	1.4
Entrée	Vegetarian	Cheese	Broccoli and Cheddar Croissant	0.96	420	870	11.00	1.6
Entrée	Vegetarian	Cheese	Cheese Bites	0.74	70	135	1.00	2.3
Entrée	Vegetarian	Cheese	Cheese Pizza	0.74	270	710	4.50	9.9
Entrée	Vegetarian		Hummus, Vegetables, Cheese, and Flatbread	1.27	497	948	7.50	0.4
Entrée	Vegetarian	Cheese	Macaroni and Cheese	0.46	213	412	4.80	1.1
Entrée	Vegetarian	Tofu	Marinated Tofu Banh Mi	0.39	206	444	0.28	0.9
Entrée	Vegetarian	Tofu	Marinated Tofu with Brown Rice	0.28	140	190	0.28	0.3
Fruit			Apple, Fresh	0.23	72	1	0.00	38.0

Fruit	Applesauce	0.23	51	2	0.00	0.1
Fruit	Assorted Chilled Fruit Cups	0.23	61	4	0.00	0.1
Fruit	Banana, Fresh	0.12	105	1	0.00	18.0
Milk	1% Plain Milk	0.21	110	130	1.50	50.0
Milk	Lactaid Milk, Fat Free	0.46	90	125	0.00	5.8
Milk	Skim Chocolate Milk	0.22	120	180	0.00	43.0
Milk	Skim Plain Milk	0.21	90	130	0.00	7.0
Vegetable	Baked Potato	0.12	139	307	1.14	0.5
Vegetable	Beans, Baked Beans	0.13	119	140	0.90	0.5
Vegetable	Beans, Chickpea Salad	0.13	151	500	0.68	3.0
Vegetable	Beans, Sizzlin' Black Beans	0.12	124	628	0.10	2.9
Vegetable	Yucca Fries, Ketchup	0.51	170	85	1.00	2.8

¹All nutrient content and cost data are per serving.

²Some entrées were not assigned a flavor profile because there was little chance that a similar entrée would be selected. This reduced unnecessary constraints.

³Menu items names are summaries of the menu item and do not list all ingredients included. Tacos included cheese, rice, and tomato salsa. Quesadillas were served with tomato salsa. All salads included ranch dressing, and entrée salads included a side of pita bread. Spaghetti, pasta, fish sandwich, jerk chicken drumstick, pulled BBQ chicken sandwich, and three bean chili are served with cheese. The yogurt grab and go included fruited yogurt, a mozzarella cheese stick, graham cracker sticks and granola.

⁴Baseline frequencies were assessed over the 2018-2019 school year and are presented as the percent of all items served by menu item category.

Table 3-2. Nutrition, cost, and repetition constraints for designing school lunch menus with minimal environmental impacts.

Constraints	Lower Bound	Upper Bound
Nutrition/Meal Pattern		
Energy (kcal)	≥ 2750	≤ 3250
Saturated fat (g)		$\leq 10\%$ of kcal
Sodium (mg)		$\leq 1,230$ on average lunch ⁻¹
Fruit (cup eq.)	≥ 2.5	
Vegetable (cup eq.)	≥ 3.75	
	Red orange	≥ 0.75
	Dark green	≥ 0.5
	Starchy	≥ 0.5
	Other	≥ 0.5
	Beans and peas	≥ 0.5
Grain (oz. eq.)	≥ 8	≤ 9
Whole grain (oz. eq.)	$\geq \frac{1}{2}$ Grains ¹	
Meat/Meat Alternative (oz. eq)	≥ 8	≤ 10
Milk (cups)	≥ 5	
Repetition Constraints		
Entrées		≤ 1
Fruits and vegetables		≤ 2
Entrée Protein Type		
	Beef	≤ 2
	Chicken	≤ 2
	Turkey	≤ 2
	Vegetarian	≤ 2
	Fish	≤ 1
Entrée Flavor Profile		
	Soy/Orange	≤ 1
	Barbecue	≤ 1
	Tomato Salsa	≤ 1
	All	≤ 1
	Spice/Turmeric	
	Salad	≤ 1
	Pasta	≤ 1
	Tofu	≤ 1
	Cheese	≤ 1
Total Weekly Components		
Entrée		=5
Fruit		=5
Vegetable		=5
Milk		=5
Weekly Waste (g)		

	10 th percentile	≤999
	15 th percentile	≤1012
	20 th percentile	≤1059
Cost (USD)		≤6.7

¹All grains served in Boston Public Schools are whole grain or whole grain rich.

Table 3-3. Optimization models for designing school lunches with minimal environmental impact.

Different combinations of objective functions and constraints were used to create weekly lunch menus. Constraints were iteratively added to objective functions.

Objective Function	Constraints	Acronym
Minimize Global Warming Potential (O1)	Nutrient and cost	MIN-GWP
Minimize Land Use (O2)	Nutrient and cost	MIN-LAND
Minimize Water Scarcity (O3)	Nutrient and cost	MIN-WATER
Minimize Marine Eutrophication Potential (O4)	Nutrient and cost	MIN-MARINE-EU
Minimize Freshwater Eutrophication Potential (O5)	Nutrient and cost	MIN-FRESH-EU
Minimize Relative Deviations from Minimum (O6)	Nutrient and cost	MIN-DEV
Minimize Environmental Impact Score (O7)	Nutrient and cost	MIN-EIS
Minimize Global Warming Potential (O1)	Nutrient, cost, and repetitions	MIN-GWP+REP
Minimize Land Use (O2)	Nutrient, cost, and repetitions	MIN-LAND+REP
Minimize Water Scarcity (O3)	Nutrient, cost, and repetitions	MIN-WATER+REP
Minimize Marine Eutrophication Potential (O4)	Nutrient, cost, and repetitions	MIN-MARINE-EU+REP
Minimize Freshwater Eutrophication Potential (O5)	Nutrient, cost, and repetitions	MIN-FRESH-EU+REP
Minimize Relative Deviations from Minimum (O6)	Nutrient, cost, and repetitions	MIN-DEV+REP
Minimize Environmental Impact Score (O7)	Nutrient, cost, and repetitions	MIN-EIS+REP
Minimize Relative Deviations from Minimum (O6)	Nutrient, cost, repetitions, and waste 10 th percentile	MIN-DEV+REP+W10
Minimize Relative Deviations from Minimum (O6)	Nutrient, cost, repetitions, and waste 15 th percentile	MIN-DEV+REP+W15
Minimize Relative Deviations from Minimum (O6)	Nutrient, cost, repetitions, and waste 20 th percentile	MIN-DEV+REP+W20

Figure 3-1. Environmental impacts of baseline and select optimized weekly menus with repetition constraints.

Environmental impacts of weekly lunch menus were determined for each optimization model and baseline menus. Figures are divided by impact category: A. Global Warming Potential, B. Land Use, C. Marine Eutrophication Potential, D. Freshwater Eutrophication Potential, and E. Water Scarcity. Columns represent the value of the environmental impact for the weekly menus developed with each model. Baseline weekly menu impacts for GWP and land use extend beyond the y-axis and are 9.5 kg CO₂ eq. and 11.6 m² crop eq., respectively.

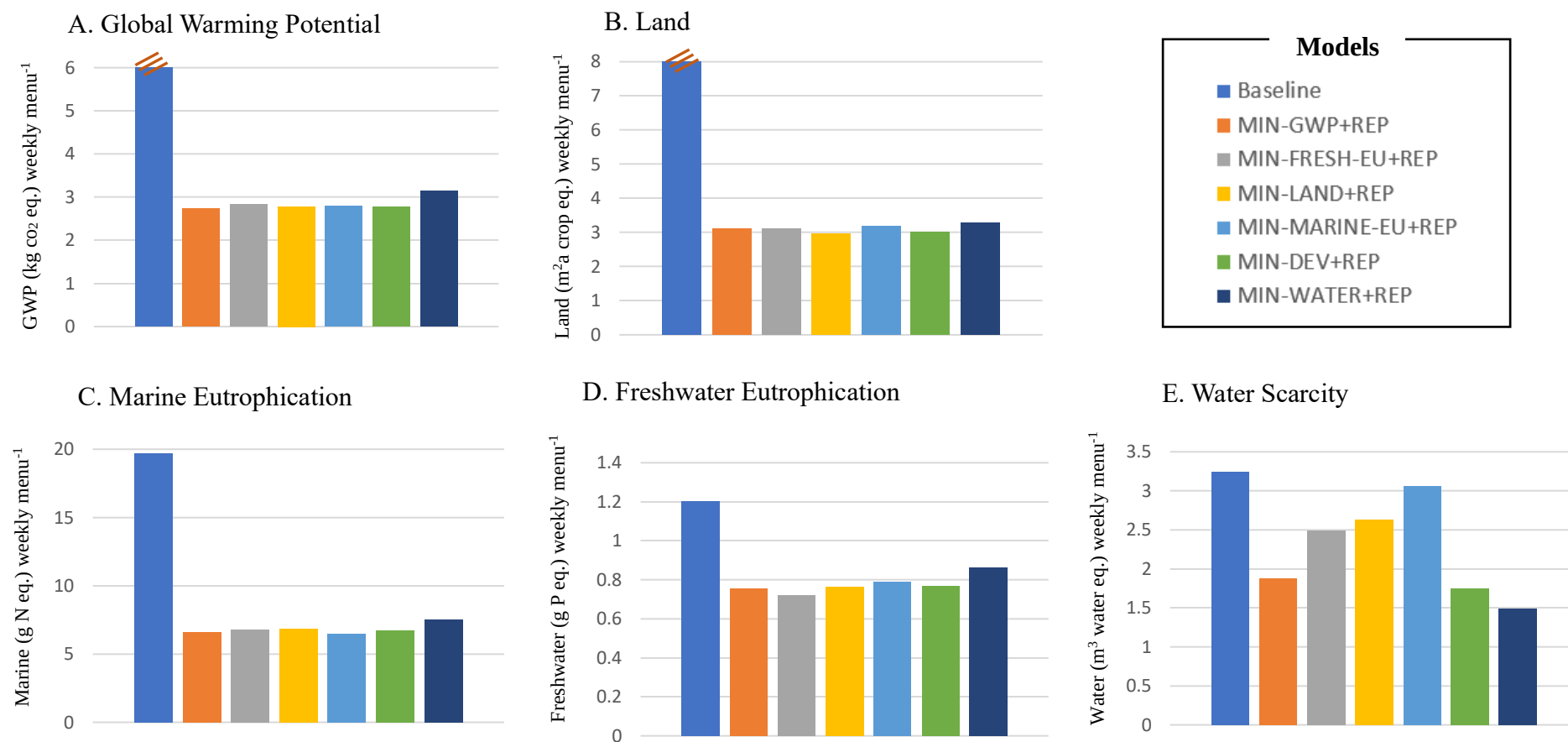


Figure 3-2. Difference (%) in student plate waste associated with select optimized weekly menus compared to baseline menus offered.

Plate waste was calculated for each optimized menu and at baseline. Waste constraints were developed using the 10th (+W10), 15th (+W15), and 20th (+W20) percentiles of baseline waste and applied to objective function O6. Columns represent the (%) difference between theoretical optimized menu waste and baseline waste. The average waste produced by weekly baseline menus was 1,291 g. Menus developed with optimization were associated with up to 23% less and 9% more waste than baseline menus.

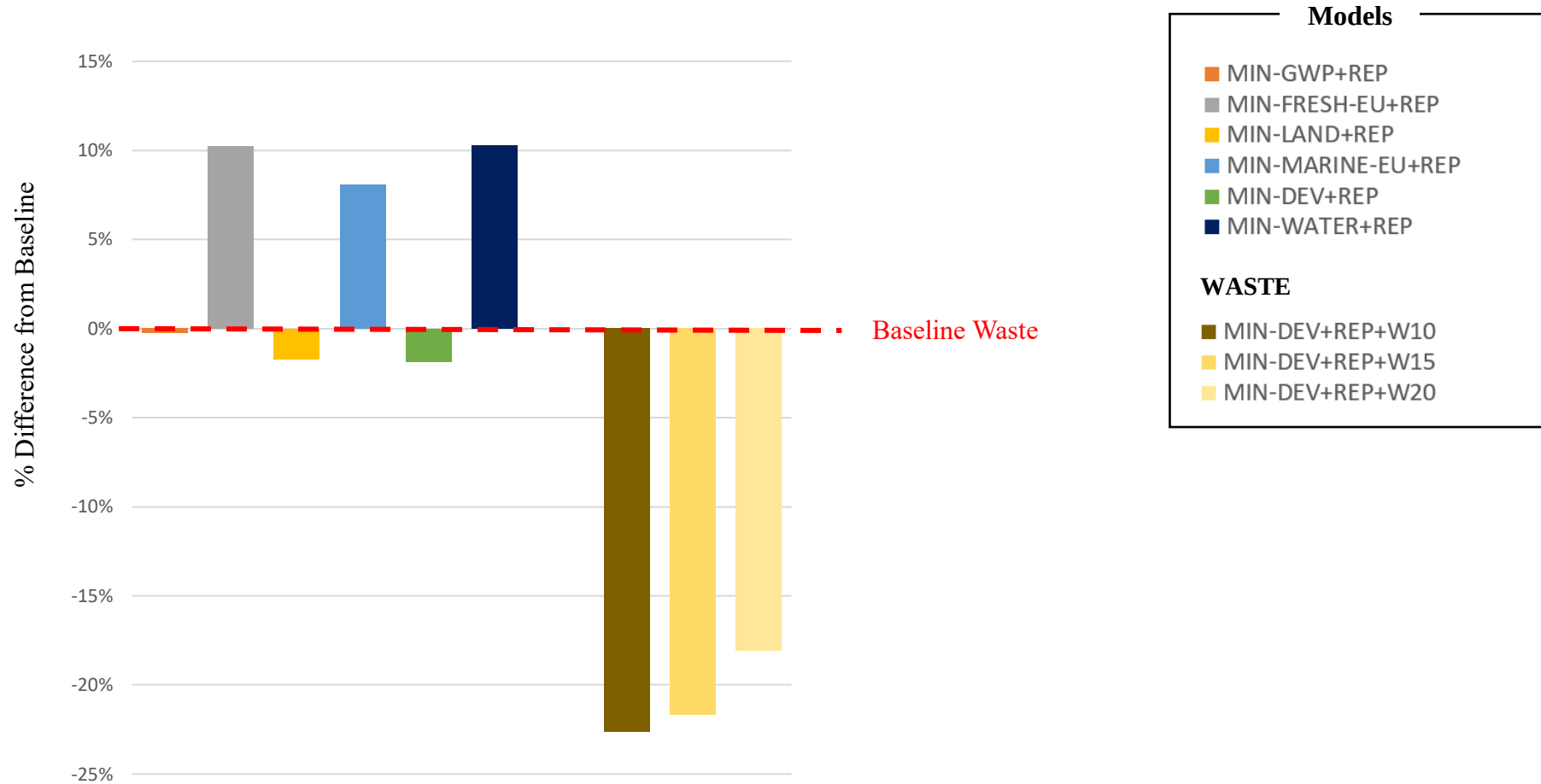


Figure 3-3. Frequency (%) of entrée protein type in baseline menus and optimized menus by objective function.

Each column represents menus offered at baseline or menus combined by objective function. For objective function columns, each column represents at least two weekly menus (e.g., Land Use (O2) = MIN-LAND and MIN-LAND+REP). Numbers on columns are the proportion of each protein type by menu.

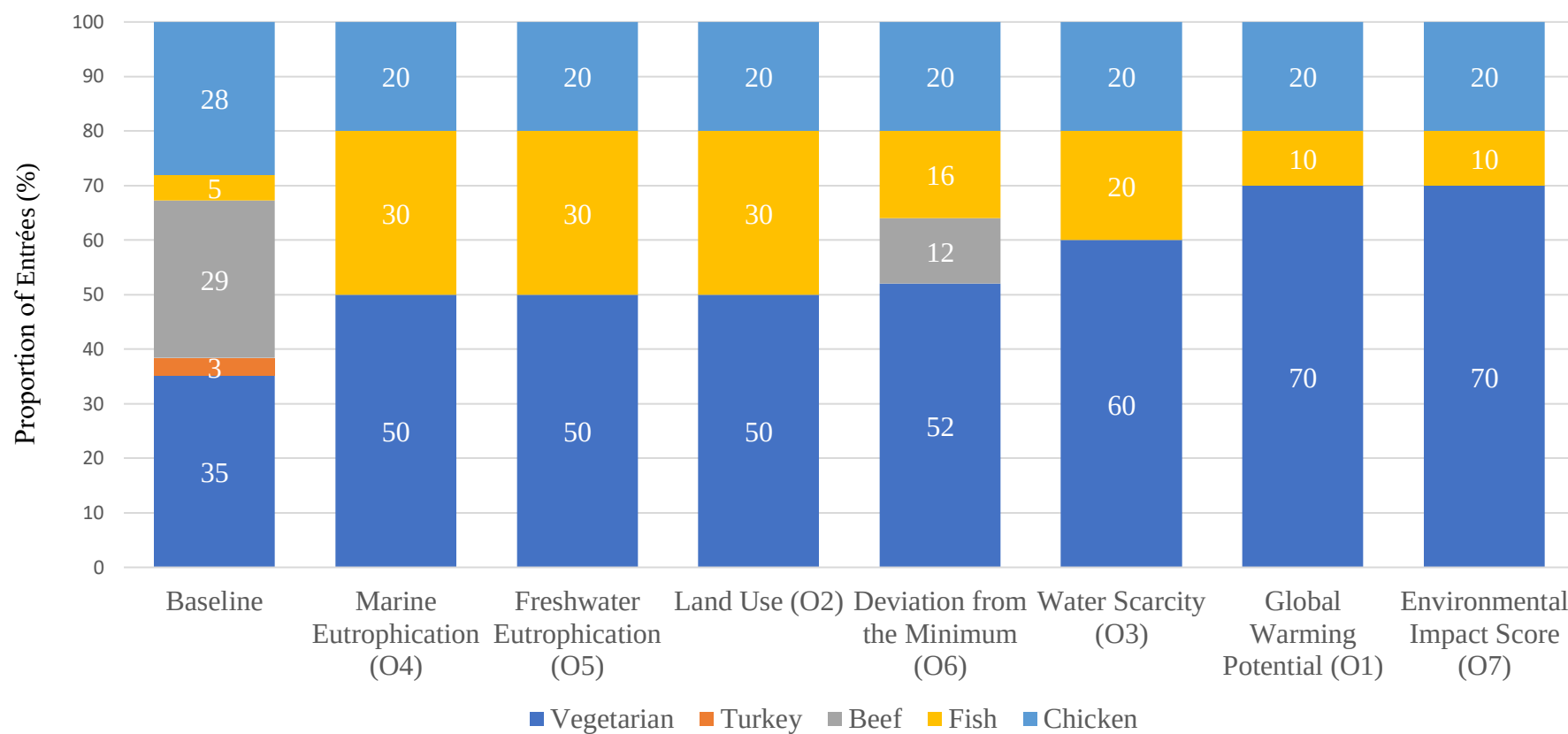
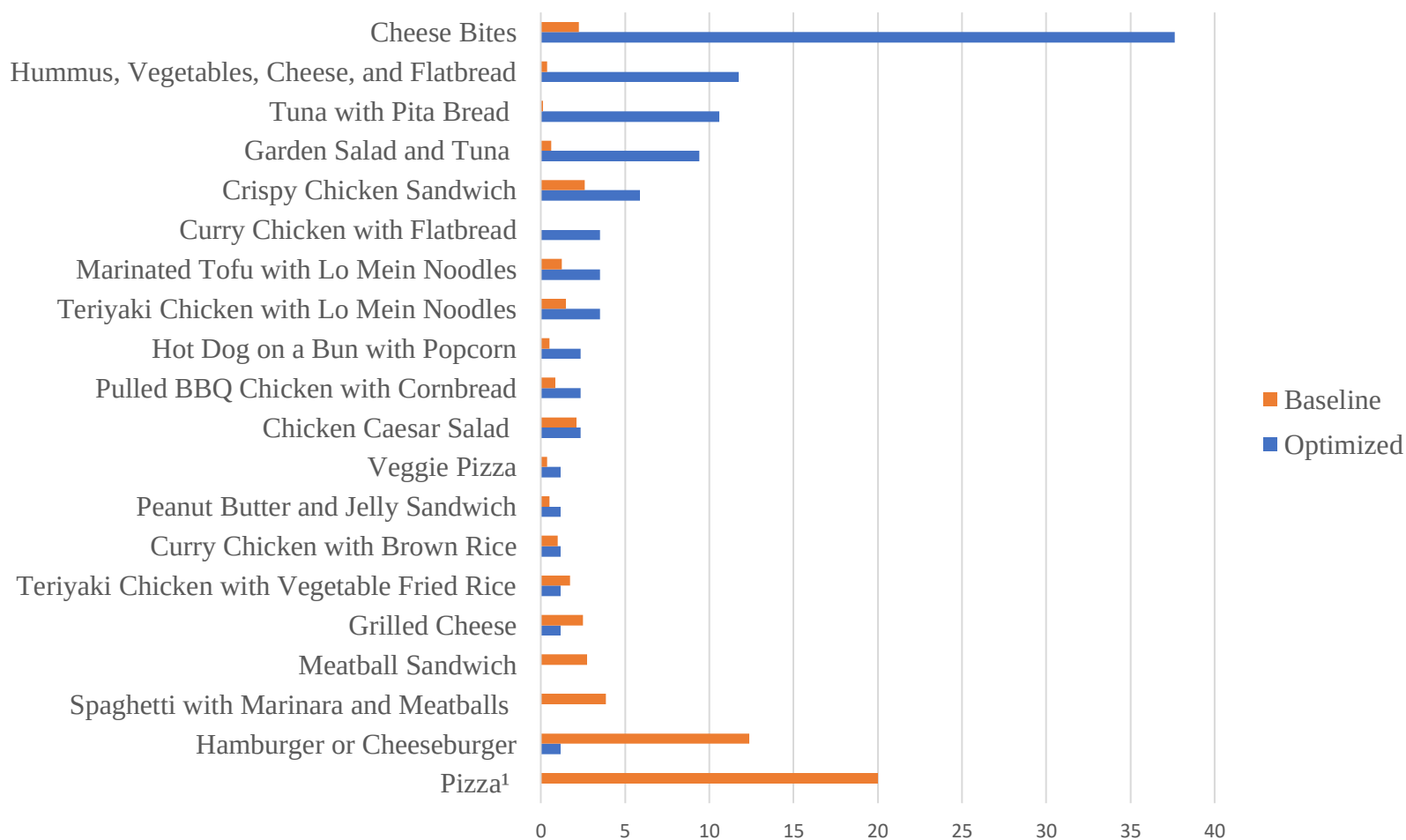


Figure 3-4. Proportion (%) of optimized and baseline menus by entrée.

Blue columns represent the proportion of an entrée in all seventeen weekly menus developed using optimization. Orange columns represent the proportion of an entrée across all baseline menus served.



¹Pizza includes all varieties of pizza.

Table 3-4. Weekly lunch menu with the lowest global warming potential subject to repetition constraints (MIN-GWP+REP).

Optimization models selected five of each meal component (entrée, fruit, vegetable, milk); meal components were combined and ordered as appropriate.

Weekday	Entrée		Fruit	Vegetable	Milk
	Subcategory 1	Item			
Monday	Chicken	Teriyaki Chicken with Lo Mein Noodles	Watermelon, Fresh	Romaine, Raw	Skim Chocolate Milk
Tuesday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Banana, Fresh	Corn, Mexican Street	Skim Chocolate Milk
Wednesday	Chicken	Crispy Chicken Sandwich	Orange, Fresh	Coleslaw	Skim Chocolate Milk
Thursday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Beans, Sizzlin' Black Beans	Skim Chocolate Milk
Friday	Vegetarian	Cheese Bites	Banana, Fresh	Sweet Potato Wedges	Skim Chocolate Milk

References

2010. The Healthy, Hunger-Free Kids Act of 2010, 111th Congress ed., USA.
- Aleksandrowicz, L., Green, R., Joy, E., Smith, P., Haines, A., 2016. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PLOS ONE* 11.
- Benvenuti, L., De Santis, A., Santesarti, F., Tocca, L., 2016. An optimal plan for food consumption with minimal environmental impact: the case of school lunch menus. *Journal of Cleaner Production* 129, 704-713.
- Blondin, S.A., Cash, S.B., Griffin, T.S., Goldberg, J.P., Economos, C.D., 2020. Meatless Monday National School Meal Program Evaluation: Impact on Nutrition, Cost, and Sustainability. *Journal of Hunger & Environmental Nutrition*, 1-13.
- Cohen, J.F., Richardson, S., Austin, S.B., Economos, C.D., Rimm, E.B., 2013. School lunch waste among middle school students: nutrients consumed and costs. *Am J Prev Med* 44(2), 114-121.
- Eustachio Colombo, P., Patterson, E., Lindroos, A.K., Parlesak, A., Elinder, L.S., 2020. Sustainable and acceptable school meals through optimization analysis: an intervention study. *Nutr J* 19(1), 61.
- Eustachio Colombo, P., Patterson, E., Schäfer Elinder, L., Lindroos, A.K., Sonesson, U., Darmon, N., Parlesak, A., 2019. Optimizing School Food Supply: Integrating Environmental, Health, Economic, and Cultural Dimensions of Diet Sustainability with Linear Programming. *Int J Environ Res Public Health* 16(17), 3019.
- FAO, 2012. Sustainable Diets and Biodiversity Directions and Solutions for Policy, Research and Action, in: Nations, F.a.A.O.o.t.U. (Ed.). Nutrition and Consumer Protection Division, FAO, FAO Headquarters, Rome, p. p.7.
- FAO and WHO, 2019. Sustainable health diets - Guiding principles. Rome.
- Gephart, J.A., Davis, K.F., Emery, K.A., Leach, A.M., Galloway, J.N., Pace, M.L., 2016. The environmental cost of subsistence: Optimizing diets to minimize footprints. *Science of The Total Environment* 553, 120-127.
- Gephart, J.A., Henriksson, P.J.G., Parker, R.W.R., Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K.,

- Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., Troell, M., 2021. Environmental performance of blue foods. *Nature* 597(7876), 360-365.
- Heller, M.C., Willits-Smith, A., Mahon, T., Keoleian, G.A., Rose, D., 2021. Individual US diets show wide variation in water scarcity footprints. *Nature Food* 2(4), 255-263.
- Heller, M.C., Willits-Smith, A., Meyer, R., Keoleian, G.A., Rose, D., 2018. Greenhouse gas emissions and energy use associated with production of individual self-selected US diets. *Environmental research letters : ERL [Web site]* 13(4), 044004.
- Kelly Thompson Nutrition Manager at Boston Public Schools, 2021. Email Correspondence on Boston Public School Lunches.
- Metcalf, J.J., Ellison, B., Hamdi, N., Richardson, R., Prescott, M.P., 2020. A systematic review of school meal nudge interventions to improve youth food behaviors. *International Journal of Behavioral Nutrition and Physical Activity* 17(1), 77.
- Pelletier, N., 2018. Changes in the life cycle environmental footprint of egg production in Canada from 1962 to 2012. *Journal of Cleaner Production* 176, 1144-1153.
- Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360(6392), 987.
- Ribal, J., Fenollosa, M., García-Segovia, P., Clemente, G., Escobar, N., Sanjuán, N., 2015. Designing healthy, climate friendly and affordable school lunches. *The International Journal of Life Cycle Assessment* 21.
- Rockström, J., Edenhofer, O., Gaertner, J., DeClerck, F., 2020. Planet-proofing the global food system. *Nature Food* 1(1), 3-5.
- Rose, D., Heller, M.C., Willits-Smith, A.M., Meyer, R.J., 2019. Carbon footprint of self-selected US diets: nutritional, demographic, and behavioral correlates. *The American Journal of Clinical Nutrition* 109(3), 526-534.
- Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., 2019. World Resources report, Creating a sustainable food future, A menu of solutions to feed nearly 10 billion people by 2050, in: Matthew, E. (Ed.). WRI.
- Stern, A., Blackstone, N.T., Economos, C.D., Griffin, T.S., 2021. Environmental impacts of the United States National School Lunch Program Communications Earth and Environment(In review).

USDA, 2019. School Nutrition and Meal Cost Study: Volume 4 - Student Participation, Satisfaction, Plate Waste and Dietary Intakes, in: Endall, J. (Ed.) School Nutrition and Meal Cost Study. Food and Nutrition Services.

USDA and HHS, 2020. Dietary Guidelines for Americans, 2020-2025, in: Services., U.S.D.o.A.a.U.S.D.o.H.a.H. (Ed.) 9th ed., Washington, D.C.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* 393(10170), 447-492.

Chapter 4 : Improving school lunch menus with multi-objective optimization: nutrition, cost, consumption, and environmental impacts.

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Abstract.

To improve school lunches in the United States, school administrators (or food service leaders) would benefit from understanding the relationships between nutritional quality, cost, student acceptance, and the environmental impacts of menus. Linear programming methods can provide school districts with insights on how these interests relate and how they might be harmonized. We used these methods to design weekly elementary school lunch menus which maximized potential consumption and nutritional quality and minimized costs and environmental impacts. Partnering with a large urban school district, menus were designed using currently available menu items and estimates of student consumption per menu item. Using single-objective models, tradeoffs were observed between most interests, but the use of multi-objective models minimized these tradeoffs. Compared to the current weekly menus offered, multi-objective models increased potential caloric intake by up to 27% and healthy eating index scores by up to 19%, and reduced costs and environmental impacts by up to 13% and 71%, respectively.

Improvements were made by reducing the frequency of beef and cheese entrées and increasing the frequency of fish and legume entrées on weekly menus. This work can be extrapolated to monthly menus to provide further direction for school districts, and the methods can be employed with different recipes and constraints. Future research should test the implementation of optimized menus in schools and consider the broader implications of implementation.

1.0 Introduction

School meal programs in the U.S. operate with varied and sometimes competing interests; meals must be low cost, nutritious, and acceptable to students. Additionally, some school districts face pressure to improve standards for sourcing and menu planning related to environmental sustainability, animal welfare, and the local economy ^(1, 2). Balancing these demands can be challenging with limited resources.

Improving the nutritional quality of school meals remains a top priority because of the prevalence of childhood obesity and its association with an increased risk for early onset disease ^(3, 4). Nearly 20% of children and adolescents in the U.S. are clinically obese, and this number is even greater for Hispanic and non-Hispanic black children ⁽⁵⁾. To improve the nutritional quality of school meals served through the U.S. National School Lunch Program (NSLP), the Healthy Hunger Free Kids Act (HHFKA) of 2010 updated school meal nutrition standards by increasing requirements for fruits, vegetables, and wholegrains and setting limits on calories and sodium ⁽²⁾. This policy undoubtedly improved the nutritional quality of school meals but raised concerns over the possibility of increased costs and student plate waste ⁽⁶⁻¹⁰⁾.

For the average school food authority in the U.S., revenues do not outweigh costs; schools run a small deficit ⁽¹¹⁾. Fortunately, financial deficits have not been associated with the HHFKA and the resulting improvements in nutrition. Conversely, better nutritional quality has been shown to increase participation rates and result in greater revenue ⁽¹¹⁻¹³⁾. However, in some cases, better nutritional quality has been linked to greater food waste ⁽¹³⁾.

Food waste is a pernicious problem, when students waste food they are not obtaining the full nutritional benefits of school meals. Additionally, when food is wasted, the limited resources embedded in the production of food such as time, money, and the natural resources used to produce foods are also wasted ^(14, 15). Annual waste from school lunch has an estimated value of over one billion USD and, on average, about one third of all milk and vegetables are wasted ^(13, 15). High waste rates might partially be explained by student dissatisfaction. In a nationally representative study, when students were asked if they liked school lunch, a majority of students

(>50%) state that “school lunch is only okay” and that they “sometimes” like the taste of the food ⁽¹³⁾. Striking balance across these interests can be challenging.

Added to these concerns is the growing pressure to incorporate environmental sustainability into menu planning ^(16, 17). The current food system uses large levels of natural resources (i.e., land and water), and contributes significantly to climate change and pollution ⁽¹⁸⁾. Dietary choice influences the magnitude of these impacts. By serving lower environmental impact lunches to children, school districts can help students develop more environmentally sustainable eating habits for the future.

Research on European school districts has started to address school meal planning challenges through linear programming and optimization. These studies focused primarily on cost and environmental outcomes, finding that menus defined using optimization could reduce greenhouse gas emissions by up to 60% while remaining within cost standards. ⁽¹⁹⁻²¹⁾.

Additionally, in a Swedish school district, when optimized menus were served, there was no difference in student satisfaction, consumption, or waste ⁽²²⁾. Using similar methods, U.S. school districts could gain insight into balancing improved nutritional quality, student acceptance, and reduced costs while managing the environmental impacts of their menus.

Given the obstacles that school districts face in harmonizing nutritional quality, cost, consumption, and environmental sustainability, the objectives of this research were to investigate how these variables interact when designing elementary school menus. Through a collaboration with a large urban school district in the Northeastern U.S., we used integer linear programming and integer goal-programming to develop weekly school lunch menus with varying goals. We then compared the modeled menus with current menus offered (baseline) to make recommendations for improving school lunch menu planning.

2.0 Methods

2.1 United States National School Lunch Program (U.S. NSLP)

The U.S. National School Lunch Program (NSLP) is a federally assisted meal program which provides nutrition standards, monetary support, and surplus foods to participating school districts. Lunches offered through this program are required to contain five meal components (meat or meat alternative, grain, vegetable, fruit, and milk) ⁽²³⁾. Additionally, there are daily or weekly requirements for fruit, vegetables, vegetable subgroups, grains, meats or meat alternatives, and fluid milk, with limits to calories, sodium, and saturated fat content. For the purposes of these analyses, we refer to the combination of meat or meat alternative and grains as an entrée.

The major form of monetary support provided by the U.S. NSLP is reimbursement per meal served. For school districts where greater than sixty percent of students participate in specific means-tested federal assistance programs, the school district receives reimbursements rates which allow the school to provide meals at no cost to all students. For the 2018-2019 school year, this rate was 3.33 USD per lunch ⁽²⁴⁾. The collaborating school district, Boston Public Schools (BPS), qualifies for this funding, provides free lunch to all students regardless of economic status, and allocates 1.34 USD per lunch for the cost of food. The remaining funds are used for staff and other operations costs.

2.2 Data

2.2.1 Menu, nutrition, and cost

Boston Public Schools (BPS) is a large urban school district in the Northeastern U.S. which serves over 50,000 students daily. The school district provided data on the cost and nutrient content of menu items offered to kindergarten through eighth grade students during the 2018-2019 school year. This included 142 menu items: 77 entrées, 18 fruit sides, 43 vegetables sides, and four milk options.

For modeling purposes, entrées were divided into two subcategories to limit the repetition of protein types (Subcategory 1, Entrée Protein Types) and provide unique flavors (Subcategory 2, Flavor Profiles) in optimized menus. Subcategory 2, Flavor Profiles, was developed after running preliminary models and finding that similar foods or flavor profiles such as chicken taco

and beef taco were often selected within the same weekly menu. While these entrées contained different protein types adding Subcategory 2, allowed for a constraint on the repetition of foods with similar ingredients or seasonings. Details of the menu items including their names, cost, nutrient content, and baseline frequency offered have been published elsewhere and are provided in the supplemental materials (Appendix C. SI Table 1) ⁽³³⁾. The methods and data used throughout this work closely align with those used in Stern et al. (2022) ⁽³³⁾.

2.2.2 Baseline menus offered

The baseline menus offered during the 2018-2019 school year were used as a comparison for menus developed using optimization. We calculated the average baseline weekly cost, nutritional quality, consumption rates, and environmental impacts of menus offered using the 2018-2019 school year menus and purchasing records. Purchasing records were used specifically for milk and fruit, because details on the types of these items were not listed on menus.

2.2.3 Consumption

The average grams consumed of each menu item were collected from 7,000 lunches served across 50 days in twelve schools during the 2018-2019 school year from baseline menus offered. This information was incorporated into optimization models to understand how consumption would change under different menu planning goals. As a modeling study, we use the term consumption to mean potential or theoretical consumption, because optimized menus were not served to students. Using this information, we present results as offered and potentially consumed and explored the relationship between these variables. Specifically, we explore the relationship between offered and consumed for energy, nutritional quality, and cost. With this comparison, we examined the efficiency of the district's budget (i.e. spending 1.34 USD per lunch but only 0.5 USD is consumed), and if offering menus with high nutritional quality led to improvements in the nutritional quality of potential intakes.

This research used standard plate waste techniques for quantifying student consumption which are described elsewhere ⁽²⁵⁾. Briefly, we measured the starting weight of foods served in grams, collected trays when students finished their lunches, and weighed any remaining food.

Consumption was calculated as the difference between the starting weight of food served and the

weight of remaining food. Consumption calculations only accounted for edible portions of foods (i.e. did not include banana peels, food packaging, etc.).

When an item was served infrequently and consumption data was limited (< 20 observations), we imputed estimates by combining data on similar items or using the 20th percentile of the proportion consumed from the respective menu item category or entrée subcategory. We used the 20th percentile because we expected consumption rates for these foods to be lower than average. These items were unique (i.e. data on similar options were not available) and served infrequently ($\leq$ ten times per year); therefore, students would be less familiar with these items and more likely to consume less. We consider this to be a highly conservative estimate. Of the 142 menu items included in the analyses, we used the 20th percentile for 21 menu items and combined data for 47 menu items (SI Table 2).

2.2.4 Global Warming Potential and Water scarcity

To quantify the environmental impacts of menus, we included data on the global warming potential (GWP) and water scarcity associated with each menu item. These impact categories were included because both have been implicated as major areas of concern associated with food production and altering dietary intakes is necessary for meeting the Paris Climate Agreement targets ^(18, 26). Additionally, previous research suggests that land use and marine eutrophication potential are strongly and positively correlated with GWP, whereas water impacts are not ⁽²⁷⁾.

Data were available from Stern et. al (2022) and Heller et. al (2021). Briefly, Stern et. al (2022) used the ecoinvent 3.6 database to estimate GWP of menu items and Heller et. al (2021) calculated water scarcity using blue water consumption from agricultural irrigation connected to geographic data and the AWARE100 method ⁽²⁹⁾. The system boundary for GWP was cradle to farm gate and water scarcity only included irrigation. As such, the GWP and water scarcity associated with the end-of-life stages for managing waste (i.e. landfilling) were not included. However, the GWP and water scarcity of producing food that would be wasted were included.

2.3 The Healthy Eating Index

We used the Healthy Eating Index (HEI) to assess the nutritional quality of baseline and optimized weekly menus. The HEI measures the proximity of a diet or menu to the recommendations in the U.S. Dietary Guidelines for Americans (DGA). The index includes 13 dietary components divided into categories to encourage or discourage (Table 1). Greater quantities of components to encourage and smaller quantities of components to discourage yield higher scores. Each component is scored separately, and the final score is the sum of the component scores. The maximum score, representing the greatest nutrition quality, is 100. Units for the meal components (cup eq. and oz. eq.) are from the U.S. DGA and compensate for the different densities of foods ⁽³⁰⁾.

2.4 Linear Programming

Linear programming and optimization are tools to find the best solution among many feasible solutions. When planning school lunches, there are numerous possible menu combinations which satisfy the NSLP requirements for nutrition and cost requirements for the district. Optimization considers the possible combinations and finds the solution which meets a particular goal. In this case, the weekly menu with the greatest nutritional quality and consumption rates and the lowest costs and environmental impacts. The standard form for linear programming is provided here:

$$\begin{aligned}
 & \text{minimize } c_1x_1 + c_2x_2 + \cdots + c_nx_n \\
 & \text{subject to constraints} \\
 & a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \geq b_1 \\
 & a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \geq b_2 \\
 & \vdots \\
 & a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \geq b_m \\
 & \text{and nonnegativity constraints} \\
 & x_1 \geq 0, x_2 \geq 0, \dots x_n \geq 0
 \end{aligned}$$

Each linear programming or optimization model includes three components: *decision variables*, *objective functions*, and *constraints*. In this study, the *decision variables* were the number of servings of each menu item selected for a weekly menu. The *objective functions* maximized consumption and nutritional quality and minimize cost and environmental impacts, and the *constraints* reduced repetitions of similar foods and were the nutrition standards and

reimbursement rates (USD) for the NSLP. A week of lunch (five days) was chosen as the unit of analysis because the U.S. NSLP guidelines are based on weekly standards and school lunch programs typically follow three- to five-week menu cycles that repeat across the school year. To consider tradeoffs across the goals we used both single and multi-objective models which are further explained in the objective function section.

We use two forms of linear programming, integer linear programming and integer goal programming, and as such all objective functions and constraints were linear. Throughout the paper we refer to these methods as optimization.

2.4.2 Constraints

All decision variables were subject to constraints to ensure that optimized menus met the nutrition requirements of the NSLP, cost less than or equal to the federal reimbursement rate provided to the district for food, and provided adequate variety across the week. Additionally, an integer constraint was applied to the decision variables to ensure that partial portions of foods were not selected. Model constraints are presented in Table 2.

Variety in school meals is important for nutrition and student acceptance, therefore we included constraints on the number of times a food could be served within the week. Each optimized weekly menu included five servings of each meal component (entrée, fruit, and milk), except for vegetables which could have up to ten servings per week, or two vegetables per lunch. This follows general practice of the school district which provides up to two vegetables options each day to meet NSLP requirements. No entrée was repeated more than once throughout the week and no more than two foods from Subcategory 1, Protein Types or one food from Subcategory 2, Flavor Profiles could be selected. This limited the model from repeatedly choosing similar foods. An exception for fish (Subcategory 1) was made; only one fish item could be selected each week because fish is not well liked by students ⁽³²⁾. Each fruit and vegetable could be repeated up to two times per week and there was no constraint on repetitions of milk type.

2.4.1 Objective Functions

We used seven objective functions to compare menus with single and/or multiple goals. The objective functions can be divided by their goals: maximize consumption (O1-O2), minimize cost (O3), maximize nutritional quality (O4), or a combination of goals, which we refer to as multi-objective functions (O5-O7).

The first objective functions (O1-O2) developed weekly menus with the greatest potential consumption. These functions maximize the total energy (kcal) consumed and total value (USD) consumed of a weekly menu and are expressed mathematically by:

Equation O1.

$$MAX f(CALCON) = \sum_{i=1}^{142} x_i * CAL_i * CON_i$$

Equation O2.

$$MAX f(COSTCON) = \sum_{i=1}^{142} x_i * COST_i * CON_i$$

where, $i = 1, \dots, 142$ represents the menu items, x_i is the decision variable and represents the number of servings of each menu item i selected, and CAL_i , CON_i , and $COST_i$ represent the energy (kcal), consumption rates, and value (USD) per serving of each menu item i , respectively. For example, per serving, a banana contains 105 kcal, costs 0.12 USD, and on average, the consumption rate is 60%. Therefore, the $CALCON$ and $COSTCON$ for a menu that only contained one banana would be 63 kcal and 0.07 USD, respectively. The objective functions find which combination of menu items yield the maximum total $CALCON$ and $COSTCON$. We were interested in maximizing the value consumed to understand how efficient the district was with its budget.

The next objective function (O3) finds the least cost weekly menu. This function minimized the total cost of a weekly menu served and is expressed mathematically by:

Equation O3.

$$MIN f(COST) = \sum_{i=1}^{142} x_i * COST_i$$

The next objective function (O4) maximized the nutritional quality of a weekly menu. While we measured the nutritional quality of menus with the HEI, the equation for HEI is nonlinear, which means that it cannot be used as an objective function in linear programming. While there are nonlinear methods for optimization, they are computationally intensive and do not guarantee that the global minimum or maximum is found. Instead, to use a linear function, we used the components and weighting of HEI with a method of goal programming which allows for the consideration of multiple variables simultaneously.

In goal programming, the objective is to minimize the sum of the relative deviations from predetermined goals. There are 13 components in the HEI, therefore, we had 13 separate goals in the nutrition objective function (O4). The goals were to maximize the components to encourage (total fruit, whole fruit, total vegetable, greens and beans, whole grains, dairy, total protein foods, seafood and plant proteins, and fatty acids) and to minimize the components to discourage (refined grains, sodium, added sugar, and saturated fats). For each component, we found the maximum or minimum possible value for a weekly lunch menu subject to constraints. For example, the goal for the greens and beans component was five cup eq., which was the maximum possible amount of dark green vegetables and legumes in a weekly menu. The objective function minimized the deviations from these goals and all deviations were standardized to manage varying scales and units by dividing by the initial goal. We then weighted each relative deviation by the maximum possible score per component in the HEI (Table 1). This function is expressed mathematically by:

Equation O4.

$$MIN f(dHEI) = \sum_{i=1}^{142} \left[\sum_{c=1}^9 \left(\frac{max_c - (x_i * encourage_{ic})}{max_c} * W_c \right) + \sum_{c=1}^4 \left(\frac{(x_i * discourage_{ic}) - min_c}{min_c} * W_c \right) \right]$$

where, $c = 1, \dots, 9$ represents the components to encourage, $c = 1, \dots, 4$ represents the components to discourage, max_c is the maximum value per weekly menu of each component to

encourage, $encourage_{ic}$ is the amount of each component in cup eq., oz. eq., or grams for each menu item, W_c is the weight of each component based on the maximum score in HEI, min_c is the minimum value per weekly menu of each component to discourage, and $discourage_{ic}$ is the amount of each component in cup eq., oz. eq., or grams for each food item.

We recognize that this method of maximizing nutritional quality does not align entirely with the HEI, as it encourages menus to go beyond the cutoff values for each component. Although we were unable to use the HEI as an objective function, we still assessed the HEI of each resulting menu and provide this information in the results.

Goal programming was also used in our final objective functions (O5-O7) to combine consumption, cost, nutritional quality, and environmental goals. We refer to the following objective functions as the *multi-objective functions* because they consider multiple disparate goals. As described above, these objective functions minimized the sum of the relative deviations from each goal. The goals for consumption, cost, and nutritional quality were calculated using the objective functions O1, O3, and O4, respectively. The goals for the environmental outcomes were the minimum global warming potential and water scarcity per weekly menu as determined in previous research ⁽³³⁾. For each goal, we applied weights to express the potential importance to a school district. This function is expressed mathematically by:

Equation O5.

$$MIN f(DEV) = \sum_{i=1}^{142} \left[\left(\frac{CONCAL_{max} - (x_i * CAL_i * CON_i)}{CONCAL_{max}} * W_{cal} \right) + \sum_{g=1}^4 \left(\frac{(x_i * z_{ig}) - min_g}{min_g} * W_g \right) \right]$$

where, $CONCAL_{max}$ is the maximum calories consumed in a weekly menu, W_{cal} is the weight applied to the relative deviation of the calories consumed goal, $g= 1, \dots, 4$ are the four goals which are minimized (cost, nutritional quality, global warming potential, and water scarcity), z_{ig} is the coefficient for each food item for each goal, min_g is the minimum value per weekly menu of each goal, and W_g is the weight applied to each of the relative deviations per goal. In this

equation, *CONCAL* is summed separately from the other goals because it is subtracting from the maximum whereas the other goals subtract the minimum.

In objective function O5, we applied equal weights to each goal ($W_{cal} = 1$ and $W_{1-4} = 1$) and in objective function O6 we applied a weight of ten to the calories consumed goal. In objective function O7 we applied a weight of 30 to the calories consumed goal, because increasing consumption is the primary goal of the district and reducing environmental impacts has been associated with improved nutritional quality ⁽³⁴⁾.

2.4.3 Models

Optimization models combine constraints and objective functions. Here, we use seven models to create and compare seven unique menus. All models were run in Microsoft Excel for Microsoft 365 MSO 16.0 in Solver with the Simplex algorithm for linear models. Table 3 lists the acronyms associated with each model used in the results. We refer to models which maximized consumption and nutritional quality while minimizing cost and environmental impacts simultaneously (O5-O7) as multi-objective models or menus, other models are referred to as single-objective models.

3.0 Results

3.1 Composition

Figure 1 shows the composition of baseline and optimized menus by entrée protein type. Baseline menus offered mostly beef (29%), chicken (28%), and vegetarian (34%) entrées, with fewer entrées containing turkey (3%) and fish (5%). All optimized menus contained chicken and vegetarian entrées. Beef entrées were only selected by the models which minimized cost (MIN-COST) and maximized consumption (MAX-CALCON, MAX-COSTCON). The models which maximized nutritional quality (MAX-HEI) and were multi-objective (MIN-DEV-CON-COST-HEI-ENV, MIN-DEV-CON10-COST-HEI-ENV, MIN-DEV-CON30-COST-HEI-ENV) included fish entrées. Overall, optimization models selected about double the proportion of legume and fish entrées and about half the proportion of cheese and beef entrées as baseline menus.

While all models selected vegetarian entrées, the types of vegetarian entrées differed across models (SI Table 3). The models which maximized consumption (MAX-CALCON, MAX-COSTCON) selected pizza and peanut butter and jelly sandwiches, whereas marinated tofu entrées were selected by the models which maximized nutritional quality (MAX-HEI) and were multi-objective (MIN-DEV-CON-COST-HEI-ENV, MIN-DEV-CON10-COST-HEI-ENV). The MIN-DEV-CON30-COST-HEI-ENV model, which weighted consumption the greatest, included both pizza and marinated tofu with brown rice.

Fresh bananas were selected for nearly all optimized menus and fresh watermelon was selected by models which maximized consumption (MAX-CALCON, MAX-COSTCON) and minimized cost (MIN-COST). Compared to baseline, the prevalence of bananas and watermelon on optimized menus was up to four times greater, but the prevalence of fresh apples was up to four times less (SI Figure 1). The most selected vegetables for optimized menus included cherry tomatoes, raw romaine lettuce, roasted red potatoes, and plantain slices (SI Figure 2). Plantain slices were selected by models which maximized consumption (MAX-CALCON, MAX-COSTCON) and multi-objective models with greater consumption weighting (MIN-DEV-CON10-COST-HEI-ENV, MIN-DEV-CON30-COST-HEI-ENV). Compared to baseline menus offered, optimized menus selected cherry tomatoes more often than sweet potato wedges, which fulfilled the vegetable subgroup requirement for red/orange vegetables. Another major difference between baseline and optimized menus was the prevalence of sweet corn, which was on optimized menus nearly four times less than baseline menus.

3.2 Consumption and Cost

Table 4 lists the average consumption rates and costs by entrée protein type, as well as the entrees with the greatest potential proportion consumed and the lowest cost per serving. There was no overlap between the ten entrées with the greatest consumption and the ten least cost entrées. On average, beef entrées had the greatest proportion consumed, followed by cheese; the least cost entrées contained legumes, followed by beef.

Menus which maximized consumption (MAX-CALCON, MAX-COSTCON) increased potential student consumption by up to 692 kcal and 1.15 USD above baseline weekly menus (Figure 2).

These increases are approximately equivalent to students consuming an extra carton of milk each day. The proportion consumed relative to the energy or value offered was also greatest for these models (75% for energy and 76% for value).

Weekly menus that minimized costs (MIN-COST) and maximized nutritional quality (MAX-HEI), had lower energy (kcal) and value (USD) consumed than baseline menus offered in absolute and relative terms (Figure 2). This suggests a potential tradeoff between maximizing consumption and nutrition and cost goals.

Baseline weekly menu costs (6.79 USD) were slightly above the allocated funds available (Figure 2). Like most other school districts in the U.S., this suggests that the district runs a small deficit. The least cost menu (MIN-COST) and multi-objective menu with equal weights (MIN-DEV-CON-COST-HEI-ENV) reduced the cost of meals by 2.60 and 0.87 USD, respectively. Extrapolated over a year, the least cost menu would provide potential savings of 93.6 USD per student, or about 5M USD for the whole of BPS. Due to the cost constraint, all other optimization models produced weekly menus which cost less than or equal to the cost constraint of 6.70 USD per weekly menu (or 1.34 USD per lunch).

3.3 Nutritional Quality

Compared to baseline menus, optimized menus which maximized nutritional quality (MAX-HEI) and were multi-objective (MIN-DEV-CON-COST-HEI-ENV, MIN-DEV-CON10-COST-HEI-ENV, MIN-DEV-CON30-COST-HEI-ENV) had 19-32% greater fiber and less added sugar (89-94%), saturated fat (51-77%), and sodium (3-26%) (SI Table 4). These optimized menus also had greater servings of total vegetables, beans and peas, dark green vegetables, plant proteins, and seafood. The HEI of these menus was up to 19% percent greater than baseline menus offered or about 16 points higher (Figure 3). Contrary to what would be expected, these optimized menus had lower total dairy and calcium than baseline menus, but this did not impact HEI because the maximum component score for dairy was met.

Menus which maximized consumption (MAX-CALCON, MAX-COSTCON) also had greater HEI than baseline menus because they contained less sodium and saturated fat per 1000 kcal (Figure 3). These differences added about eight additional points to the HEI of these menus.

While there appeared to be a tradeoff between maximizing consumption and nutritional quality, this result suggests that nutrition and consumption might be more aligned than previously expected. The model which minimized cost, however, had the lowest HEI and was three points below baseline offerings, highlighting that nutritional quality and cost minimization are possibly at odds.

The potential HEI consumed was calculated using the components consumed and energy offered. Although the MAX-HEI and MIN-DEV-CON10-COST-HEI-ENV models had the greatest HEI offered, the MIN-DEV-CON-COST-HEI-ENV model had the greatest HEI consumed (Figure 3). Consumption of essential nutrients also differed across modeled menus. In most cases, the models which maximized consumption and were multi-objective with greater consumption weighting (MAX-CALCON, MAX-COSTCON, MIN-DEV-CON10-COST-HEI-ENV, MIN-DEV-CON30-COST-HEI-ENV) resulted in greater absolute and relative consumption of important nutrients such as fiber, calcium, and iron, compared to the MAX-HEI model (SI Table 4). For example, the MIN-DEV-CON10-COST-HEI-ENV menu had the highest potential fiber consumption (32 g) but offered less fiber than the model which maximized HEI.

3.4 Environmental Impacts

Menus which maximized nutritional quality (MAX-HEI) and were multi-objective (MIN-DEV-CON-COST-HEI-ENV, MIN-DEV-CON10-COST-HEI-ENV, MIN-DEV-CON30-COST-HEI-ENV) reduced global warming potential and water scarcity by on average 67% and 46% compared to baseline, respectively (Figure 4). The multi-objective weekly menu with equal weights (MIN-DEV-CON-COST-HEI-ENV) was the most effective at reducing global warming potential and water scarcity and had the greatest HEI consumed of all models, suggesting synergy between reducing environmental impacts and maximizing nutritional quality. In most cases the other models maintained or increased environmental impacts above baseline menus offered, suggesting that reducing costs and increasing consumption in this context do not necessarily promote environmental sustainability.

4.0 Discussion

This research designed elementary school lunch menus with improved nutritional quality, increased potential consumption rates, lower costs, and reduced environmental impacts using linear programming and optimization. Menus which maximized nutritional quality did not necessarily result in the greatest potential consumption of important nutrients or the greatest potential HEI consumed. As such, incorporating consumption rates into optimization models could be essential to ensuring that improved nutrition is realized. Tradeoffs between cost, consumption, and nutrition were apparent when modeling menus with single objectives. Multi-objective menus minimized these tradeoffs and produced improvements across all goals compared to baseline. School districts struggling to meet multiple objectives when menu planning can use similar tools to design superior menus, balance competing interests, and better understand tradeoffs.

4.1 Nutrition and Consumption

Using optimization to design school lunch menus might offer meaningful nutritional gains. During the 2014-2015 school year, the average HEI for elementary school lunch menus was 82⁽⁷⁾. By comparison, the HEI of lunches brought from home and of the overall diets of children and adolescents were significantly lower, 65 and 54, respectively^(7, 35). Baseline results for this study were similar to the national average and suggest that the school district is already providing meals which have superior nutritional quality to foods from home or eaten outside of school. However, this research shows that altering the frequency of menu items currently offered could further improve the nutritional quality of lunches. In adults, increases in dietary HEI are associated with improved health outcomes, including a reduced risk of all-cause mortality, and scores above 81 are associated with a reduced risk of obesity^(36, 37). Optimization increased the HEI of weekly menus from 84 at baseline to 100, and the HEI of the consumed portion from 77 at baseline to 94. As such, instituting optimized menus could provide potential health benefits to students. Optimized menus had greater HEIs than baseline menus because they included more fish, legumes, and vegetables, and less beef, cheese, sodium, and saturated fat.

While optimization successfully developed menus with greater nutritional quality, greater nutrients offered did not always result in greater nutrients consumed. Menu planning which

incorporates consumption could offer greater nutritional value to students than menus designed to solely enhance nutritional quality. This was clearly illustrated with fiber; the model which maximized nutritional quality (MAX-HEI) offered the most fiber, but potential fiber consumption was greatest for the multi-objective menus with consumption weighting (MIN-DEV-CON10-COST-HEI-ENV, MIN-DEV-CON30-COST-HEI-ENV). While this finding might seem to suggest that greater nutritional quality was associated with greater waste, this was not necessarily the case. Our research shows that menus which maximized consumption had higher nutritional quality than baseline menus. This is confirmed by previous research which finds that improved nutritional quality can increase consumption rates for certain meal categories including entrées and vegetables ^(38, 39).

Given the current levels of plate waste in the U.S. NSLP, up to 30% for certain food categories, and the implications of waste, it is imperative to increase school lunch consumption rates. Here we found that the types of menu items served impact potential consumption rates and that these consumption rates can be improved simultaneously with nutritional quality. Like previous research, we identified considerable variability in consumption rates across meal components and entrée protein type, with vegetables and legumes having some of the lowest consumption rates ^(13, 38). Although similar data collection methods were employed, the consumption rates used in this research were on average nearly 19% lower than national average estimates ⁽¹³⁾. This is partially explained by our conservative imputation methods. While differences in consumption rates were stark, the consumption data used for this research were collected from a larger sample than national estimates, offered consistently more conservative estimates, and reflected the school district of interest.

4.3 Cost and Environmental Impacts

After the implementation of HHFKA, school food authorities reported that the most significant challenge when planning meals was the cost of foods ⁽⁴⁰⁾. Here, we showed that nutritious lunches with potentially higher student consumption can result in costs within or below budget constraints. This is particularly relevant for the studied school district and the many school districts which run small deficits, as these methods could be used to help maintain budgets while managing other goals. Like previous research, we found that more nutritious lunches did not cost

more to produce ⁽¹¹⁾. However, the least cost menu had the lowest HEI and was below the HEI of baseline weekly menus, which suggests a tradeoff between minimizing cost and maximizing nutritional quality.

Previous research using optimization to design school lunch menus has focused on environmental impacts ⁽¹⁹⁻²¹⁾. This study additionally integrated concerns pertinent to the U.S. NSLP and was still able to reduce environmental impacts of weekly lunch menus. The reduction observed here most likely resulted from limiting beef and cheese entrées.

The multi-objective models had the lowest environmental impacts. These models also had the greatest nutritional quality apart from the model which maximized nutritional quality. This aligns with previous research which found that improved diet quality is correlated with reduced environmental impacts ^(34, 41, 42). Although this relationship has been previously reported, it is not causal and school districts should be cautious with assumption about this connection because it is not always true for all impacts and foods, (i.e. refined sugar has low global warming potential but is discouraged when assessing diet quality).

4.4 Recommendations

Numerous studies have used optimization to balance environmental, health, cost, and cultural components of diet ^(43, 44). Like this work, these studies found that optimized diets were more plant-based, reduced beef and lamb, in some cases increased fish, and reduced sweets and refined grain bread.

The multi-objective models were most successful in minimizing tradeoffs and can be used to inform future menu planning. Additionally, the distribution of all model entrée protein types (Figure 1) provides an outline for recommendations. If our results were extended across the month, entrées containing legumes would appear about once a week, fish entrées would appear every other week, beef and cheese entrées would be offered up to three times a month each, and chicken would be offered six times a month.

This outline would require reductions in beef and cheese entrées compared to baseline offerings. Baseline menus offered beef and cheese because they were inexpensive and highly consumed. Even with their high consumption rates, we show that removing or reducing beef and cheese from menus can increase consumption rates by up to about 400 calories per week. Nonetheless, complete removal of beef from menus could be difficult and school districts should consider reducing beef entrées slowly, with the goal of offering it every other week or in smaller portions.

Some of the lowest consumption rates for entrées were for non-pizza vegetarian dishes, yet optimization models repeatedly selected these options. As such, careful planning of vegetarian entrées, slow or gradual introduction, and offering taste tests, interactive cooking demonstrations, or other interventions might be necessary to improve consumption rates and acceptance ⁽⁴⁵⁾. The federal government could support this change by requiring weekly non-pizza vegetarian entrées and pairing changes with grants to support interventions and education.

4.5 Limitations and Future Directions

Limitations to this research arose from both the tools used to design menus and data availability. Linear programming did not allow for the maximization of HEI. Using goal programming methods seemed to successfully produce a maximum value for HEI, however, the MIN-DEV-CON10-COST-HEI-ENV menu had a higher HEI than the MAX-HEI model. In terms of data availability, multiple options for each meal component are available to students daily and the school district does not keep records on student selections. Baseline measurements were based on what was offered to students on the menu, even though certain items might be selected less frequently. Students are more likely to select items that they like which might lead to greater consumption. As such, our baseline average consumption estimate was most likely lower than actual average weekly consumption rates. Similarly, the average nutritional quality of weekly baseline menus was most likely slightly inflated. Without selection data it is not feasible to assess these values. Ultimately, this work informs menu planning and future research can be designed to incorporate student selection.

Additionally, this research did not include information on produce seasonality or environmental impacts beyond the farm gate. The models selected produce, such as watermelon, which might

only be available seasonally. To make the changes suggested, the district will need to consider what products are available in greater quantities and in which seasons. Future analyses could incorporate information on procurement. As mentioned in the methods, the environmental data only included water scarcity and GWP, and the system boundaries for this data did not include waste management. While the impacts of waste management are expected to be lower than those used to produce food, including waste management would provide a more complete picture of the impacts of meals and food waste. Also, this analysis did not include impacts relevant to fisheries management such as biodiversity. Including this information is important to better understand the environmental impacts of menu items which contain tuna.

Moving forward, research should assess the impact of implementing optimized menus as has been performed in Swedish schools ⁽²²⁾. This research could be coupled with various forms of interventions to increase consumption and acceptance of new menus. Research informing implementation will be essential to ensuring that the benefits of optimized menus are realized and that unintended consequences are avoided. Additionally, future modeling studies could consider the shadow prices of constraints, and how constraints could be altered to further improve menus.

5.0 Conclusion

Optimization and linear programming are effective tools for designing school lunch menus with multiple objectives. These methods allowed for the minimization of tradeoffs across goals and weighting based on priorities for the school district. Compared to weekly baseline menus offered, menus designed with multi-objective models increased potential energy consumption by up to 27% and HEI by up to 19%, and reduced costs and environmental impacts by up to 13% and 71%, respectively. Improvements were made by reducing the frequency of beef and cheese entrées and increasing the frequency of fish and legume entrées on weekly menus. This work can be extrapolated to monthly menus to provide further direction for school districts and the methods can be employed with different recipes and constraints. In the future, implementation studies should test student acceptance of optimized menus and consider how to increase acceptance of nutritious, low-cost, and low-impact items such as legumes.

Table 4-1. Components and scoring for the Healthy Eating Index 2015¹.

Component	Maximum Points		Standard for Minimum Score
Adequacy			
Total Fruit ²	5	≥ 0.8 cup eq. per 1,000 kcal	No Fruit
Whole Fruit ³	5	≥ 0.4 cup eq. per 1,000 kcal	No Whole Fruit
Total Vegetable ⁴	5	≥ 1.1 cup eq. per 1,000 kcal	No Vegetables
Greens and Beans ⁴	5	≥ 0.2 cup eq. per 1,000 kcal	No Dark-Green Vegetables or Legumes
Whole Grains	10	≥ 1.5 oz. eq. per 1,000 kcal	No Whole Grains
Dairy ⁶	10	≥ 1.3 cup eq. per 1,000 kcal	No Dairy
Total Protein Foods ⁴	5	≥ 2.5 oz. eq. per 1,000 kcal	No Protein Foods
Seafood and Plant Proteins ^{4,6}	5	≥ 0.8 oz. eq. per 1,000 kcal	No Seafood or Plant Proteins
Fatty Acids	10	(PUFAs + MUFAs)/SFAs ≥ 2.5	(PUFAs + MUFAs)/SFAs ≤ 1.2
Moderation			
Refined Grains	10	≤ 1.8 oz. eq. per 1,000 kcal	≥ 4 oz. eq. per 1,000 kcal
Sodium	10	≤ 1.1 grams per 1,000 kcal	≥ 2 g per 1,000 kcal
Added Sugars	10	≤ 6.5% of energy	≥ 26% of energy
Saturated Fats	10	≤ 8% of energy	≥ 16% of energy

PUFA = Polyunsaturated fatty acid; MUFA = Monounsaturated fatty acid; SFA = Saturated fatty acid

¹Intakes between the minimum and maximum standards are scored proportionately.

²Includes 100% fruit juice.

³Includes all forms except juice.

⁴Includes legumes (beans and peas).

⁵Includes all milk products, such as fluid milk, yogurt, and cheese, and fortified soy beverages.

⁶Includes seafood, nuts, seeds, soy products (other than beverages), and legumes (beans and peas).

⁷Ratio of poly- and mono-unsaturated fatty acids (PUFAs and MUFAs) to saturated fatty acids (SFAs).

Table 4-2. Nutrition, cost, and repetition constraints for school lunch models.

Constraints		Lower Bound	Upper Bound
Nutrition/Meal Pattern			
Energy (kcal)		≥ 2750	≤ 3250
Saturated fat (g)			$\leq 10\%$ of kcal
Sodium (mg)			$\leq 1,230$ on average lunch ⁻¹
Fruit (cup eq.)		≥ 2.5	
Vegetable (cup eq.)		≥ 3.75	
	Red orange	≥ 0.75	
	Dark green	≥ 0.5	
	Starchy	≥ 0.5	
	Other	≥ 0.5	
	Beans and peas	≥ 0.5	
Grain (oz. eq.)		≥ 8	≤ 9
Whole grain (oz. eq.)		$\geq \frac{1}{2}$ Grains ¹	
Meat/Meat Alternative (oz. eq)		≥ 8	≤ 10
Milk (cups)		≥ 5	
Repetition Constraints			
Entrées			≤ 1
Fruits and Vegetables			≤ 2
Entrée Protein Types			
	Beef		≤ 2
	Chicken		≤ 2
	Turkey		≤ 2
	Vegetarian		≤ 2
	Fish		≤ 1
Entrée Flavor Profiles			
	Soy/Orange		≤ 1
	Barbecue		≤ 1
	Tomato Salsa		≤ 1
	All Spice/Turmeric		≤ 1
	Salad		≤ 1
	Pasta		≤ 1
	Tofu		≤ 1
	Cheese		≤ 1
Total Weekly Components			
	Entrée		$= 5$
	Fruit		$= 5$
	Vegetable		$= 10^2$
	Milk		$= 5$
Cost (USD)			≤ 6.7

¹All grains served in Boston Public Schools are whole grain or whole grain rich.

²The school district offers up to two vegetables each day to meet vegetable subgroup requirements.

Table 4-3. Optimization models for balancing cost, nutritional quality, consumption, and environmental impacts.

Objective Function		Acronym
Single-Objective Models (menus)		
O1	Maximize energy (kcal) consumed	MAX-CALCON
O2	Maximize value (USD) consumed	MAX-COSTCON
O3	Minimize cost (USD)	MIN-COST
O4	Maximize nutritional quality (HEI Components)	MAX-HEI
Multi-Objective Models (menus)		
O5	Minimize deviations of goals (Energy consumed, Cost, HEI, and Environmental Impacts)	MIN-DEV-CON-COST-HEI-ENV
O6	Minimize deviations of goals (Energy consumed, Cost, HEI, and Environmental Impacts) with consumption weights x 10	MIN-DEV-CON10-COST-HEI-ENV
O7	Minimize deviations of goals (Energy consumed, Cost, HEI, and Environmental Impacts) with consumption weights x 30	MIN-DEV-CON30-COST-HEI-ENV

Figure 4-1. Composition of optimized and baseline menus by entrée protein type.

The proportion of each entrée protein type was determined for baseline and optimized weekly menus and all optimized weekly menus combined (All Models). Each bar represents the entrées selected by the models or at baseline. Each optimized menu included five entrées, all models combined represents 35 entrées, and the baseline column includes 800 entrées. Different colors distinguish the protein types, with vegetarian proteins in shades of orange and poultry in shades of blue.

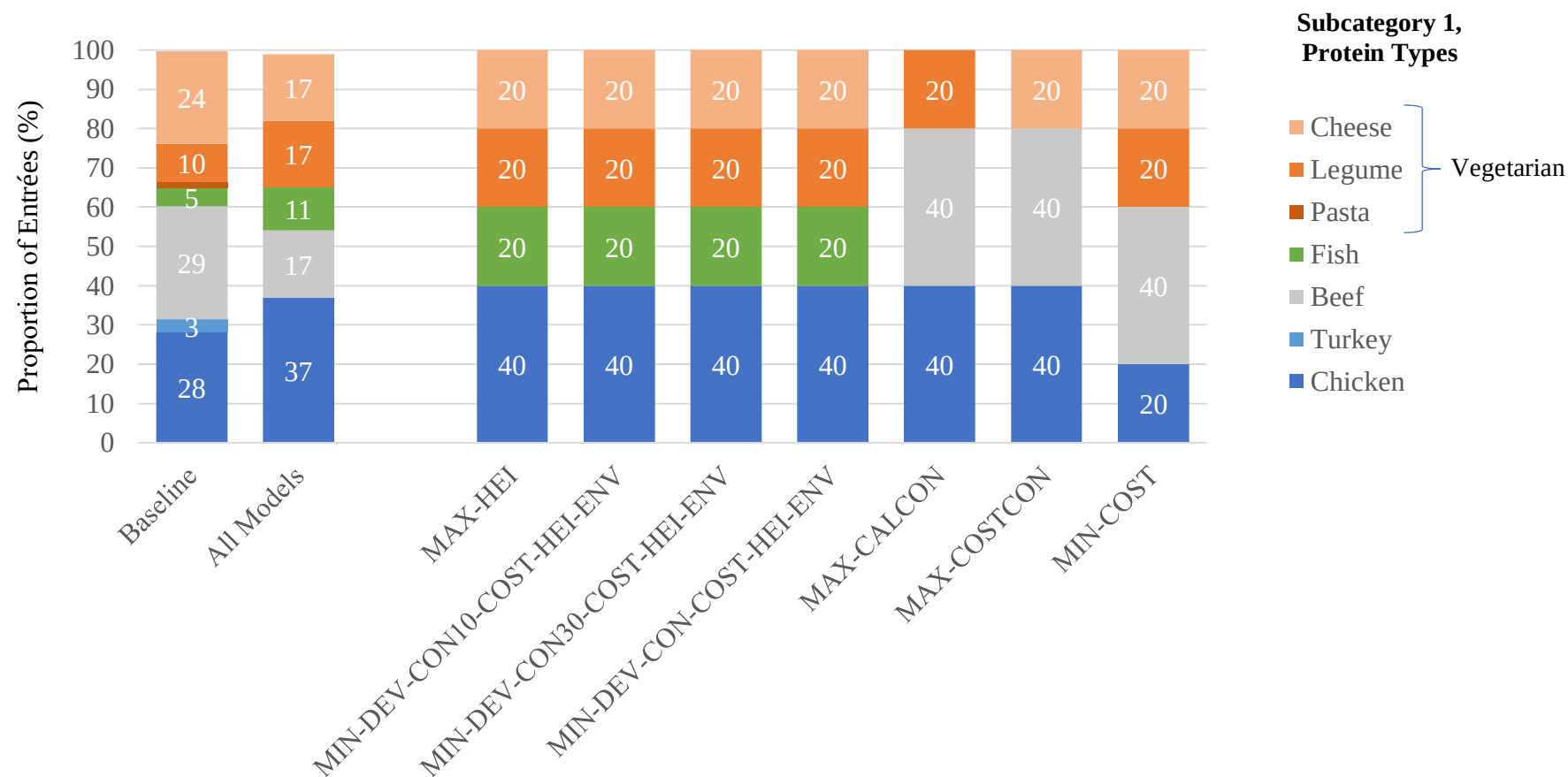


Table 4-4. Average consumption rates and cost by entrée protein type and entrées with the greatest consumption (%) and lowest costs (USD).

Entrée Protein/Entrée	Avg. Consumption (%) ¹	Cost (USD serving ⁻¹)
Beef	68	0.66
Chicken	57	0.88
Fish	59	0.91
Turkey	50	1.10
Vegetarian	52	0.71
Cheese	67	0.75
Pasta	40	1.36
Legume	43	0.56
Greatest Consumption (Descending Order)		
Hot Dog on a Bun with Popcorn	88	0.99
Meatball Pizza	87	0.74
Veggie Pizza	85	0.74
Cheese Pizza	84	0.74
White Garlic Pizza	84	0.74
Chicken Tenders with Cheese Bites	79	1.2
Pulled BBQ Chicken with Cornbread	78	0.8
Pulled BBQ Chicken Sandwich	78	0.55
Cheese Bites	77	0.74
Meatballs and Garlic Bread	76	0.52
Least Cost (Ascending Order)		
Marinated Tofu with Brown Rice	40	0.28
Hamburger	71	0.29
Marinated Tofu with Lo Mein Noodles	40	0.29
Cheeseburger	71	0.34
Grilled Cheese	57	0.37
Three Bean Chili with Tortilla Chips	60	0.38
Seasoned Chicken and Brown Rice	46	0.4
Marinated Tofu with Vegetable Fried Rice	40	0.41
Toasted Cheese Sandwich and Three Bean Chili	53	0.45
Macaroni and Cheese	62	0.46

¹Consumption was calculated as the average grams consumed divided by the average starting weight.

Figure 4-2. Energy (kcal) and cost (USD) offered and consumed of baseline and optimized weekly menus.

Energy and cost, offered and consumed, were determined for optimized and baseline weekly menus. Figures are divided into absolute and relative results for energy and cost/value: A. Absolute Energy, Offered and Consumed (kcal), B. Relative Energy Consumed, C. Absolute Cost, Offered and Consumed (USD), and D. Relative Value Consumed. Full columns (including dark and light shading) represent energy and cost of weekly menus offered and lighter shading represents the proportion of energy or value consumed. Values in white inside of columns are the absolute and relative energy and value consumed.

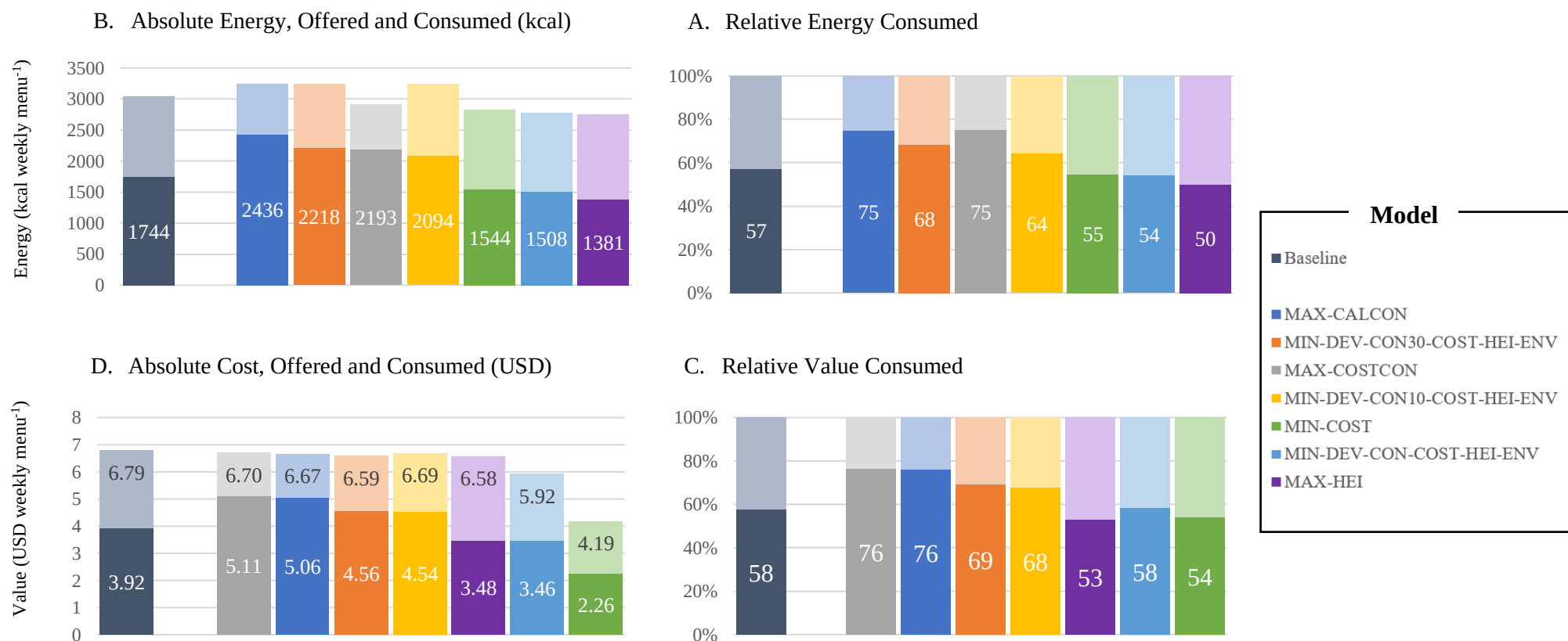


Figure 4-3. Healthy Eating Index (HEI) of baseline and optimized weekly menus, as offered and consumed.

Columns represent the HEI of baseline and optimized weekly menus, with darker shaded portions of columns representing the HEI of the consumed portion. Labels for the HEI of the consumed portion are in white and labels for the HEI offered are in black. The y-axis starts at 70 to emphasize differences.

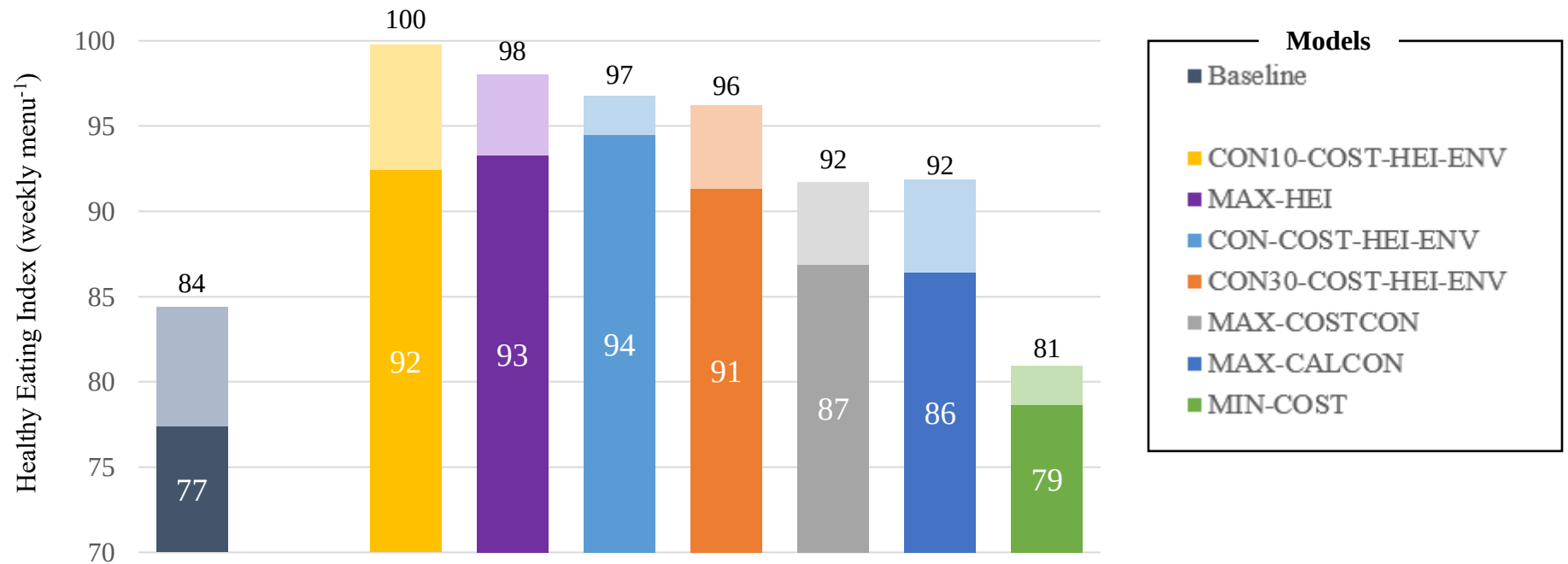
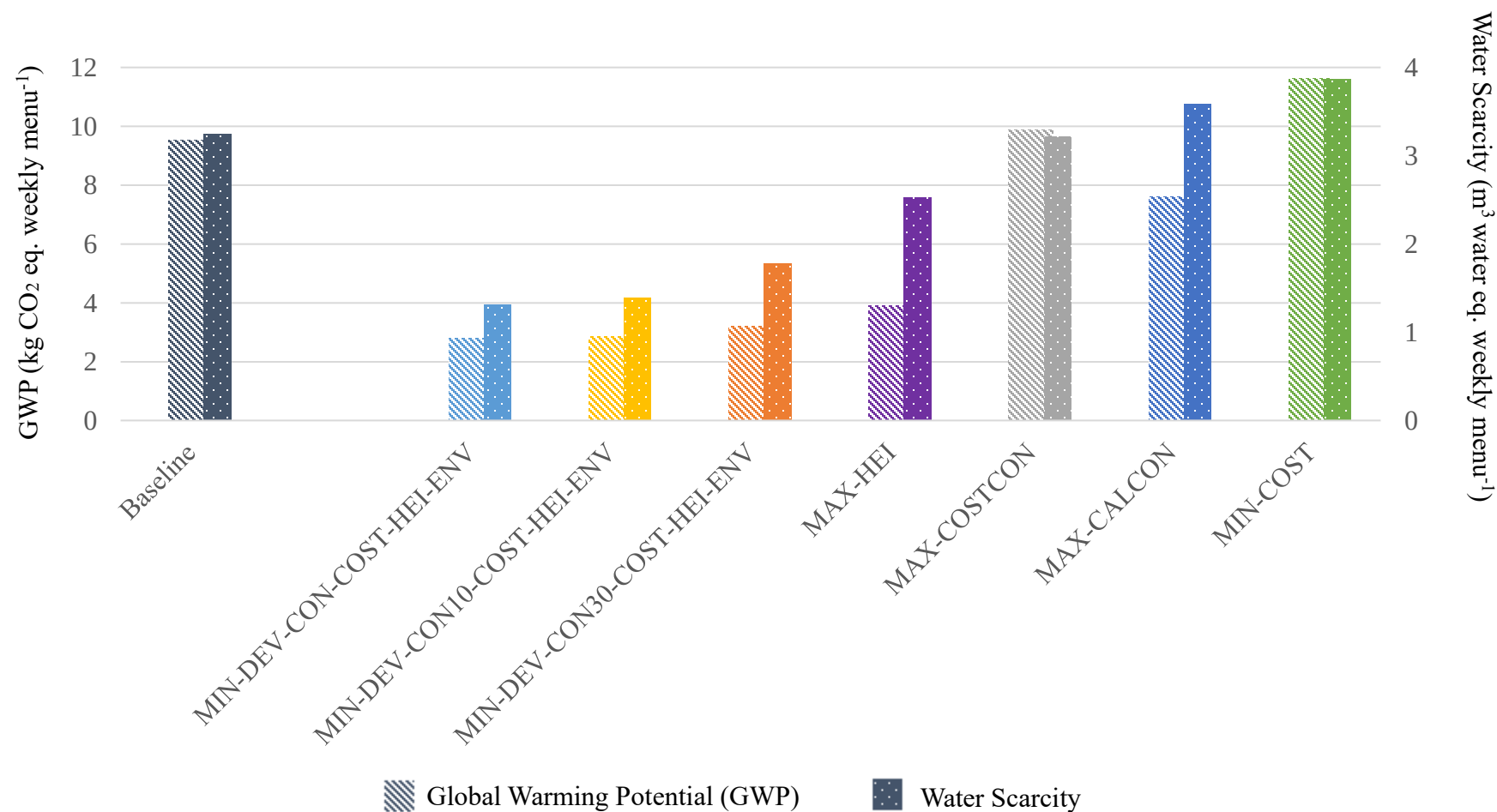


Figure 4-4. Global warming potential (GWP) and water scarcity of baseline and optimized weekly menus.

Columns with stripes represent the GWP (kg CO₂ eq.), and columns with dots represent water scarcity (m³ water eq.) of baseline and optimized weekly menus.



References

1. Center for Good Food Purchasing (2017) Good Food Purchasing Standards 2.0 – September 2017 Update. <https://goodfoodpurchasing.org/good-food-purchasing-standards-update-september-2017/#value-category-updates>
2. (2010) The Healthy, Hunger-Free Kids Act of 2010, 111th Congress ed. USA.
3. Lloyd LJ, Langley-Evans SC McMullen S (2012) Childhood obesity and risk of the adult metabolic syndrome: a systematic review. *Int J Obes (Lond)* 36, 1-11.
4. Park MH, Falconer C, Viner RM *et al.* (2012) The impact of childhood obesity on morbidity and mortality in adulthood: a systematic review. *Obesity Reviews* 13, 985-1000.
5. CDC (2019) Childhood Obesity Facts | Overweight & Obesity | CDC.
6. Gearan EC & Fox MK (2020) Updated Nutrition Standards Have Significantly Improved the Nutritional Quality of School Lunches and Breakfasts. *Journal of the Academy of Nutrition and Dietetics* 120, 363-370.
7. USDA (2019) *School Nutrition and Meal Cost Study: Volume 2 - Nutritional Characteristics of School Meals*. School Nutrition and Meal Cost Study. Food and Nutrition Services.
8. Kogan R (2019) Rollback Of Nutrition Standards Not Supported By Evidence. In *Health Affairs*.
9. Buscemi J, Odoms-Young A, Yaroch AL *et al.* (2018) Position Statement: Retain School Meal Standards and Healthy School Lunches: Society of Behavioral Medicine.
10. Mitka M (2012) Meal Programs Questioned. *JAMA* 308, 1849-1849.
11. USDA (2019) *School Nutrition and Meal Cost Study: Volume 3 - School Meal Costs and Revenues*. School Nutrition and Meal Cost Study. Food and Nutrition Services.
12. Wojcicki JM & Heyman MB (2006) Healthier Choices and Increased Participation in a Middle School Lunch Program: Effects of Nutrition Policy Changes in San Francisco. *Am J Public Health* 96, 1542-1547.
13. USDA (2019) *School Nutrition and Meal Cost Study: Volume 4 - Student Participation, Satisfaction, Plate Waste and Dietary Intakes*. School Nutrition and Meal Cost Study. Food and Nutrition Services.

14. Blondin SA, Cash SB, Goldberg JP *et al.* (2017) Nutritional, Economic, and Environmental Costs of Milk Waste in a Classroom School Breakfast Program. *Am J Public Health* 107, 590-592.
15. Cohen JF, Richardson S, Austin SB *et al.* (2013) School lunch waste among middle school students: nutrients consumed and costs. *Am J Prev Med* 44, 114-121.
16. Poole MK, Musicus AA Kenney EL (2020) Alignment Of US School Lunches With The EAT-Lancet Healthy Reference Diet's Standards For Planetary Health. *Health Affairs* 39, 2144-2152.
17. Kraus-Polk J & Hamerschlag K (2021) The State of School Lunch in California: Opportunities for Improving the Health and Environmental Profile of School Food [Friends of the Earth, editor].
18. Rockström J, Edenhofer O, Gaertner J *et al.* (2020) Planet-proofing the global food system. *Nature Food* 1, 3-5.
19. Eustachio Colombo P, Patterson E, Schäfer Elinder L *et al.* (2019) Optimizing School Food Supply: Integrating Environmental, Health, Economic, and Cultural Dimensions of Diet Sustainability with Linear Programming. *Int J Environ Res Public Health* 16, 3019.
20. Ribal J, Fenollosa M, García-Segovia P *et al.* (2015) Designing healthy, climate friendly and affordable school lunches. *The International Journal of Life Cycle Assessment* 21.
21. Benvenuti L, De Santis A, Santesarti F *et al.* (2016) An optimal plan for food consumption with minimal environmental impact: the case of school lunch menus. *Journal of Cleaner Production* 129, 704-713.
22. Eustachio Colombo P, Patterson E, Lindroos AK *et al.* (2020) Sustainable and acceptable school meals through optimization analysis: an intervention study. *Nutr J* 19, 61.
23. USDA (2012) Nutrition Standards in the National School Lunch and School Breakfast Programs. In *Federal Register / Vol 77, No 17* [FaNSF USDA, editor].
24. USDA (2018) National School Lunch, Special Milk, and School Breakfast Programs, National Average Payments/Maximum Reimbursement Rates vol. *Federal Register / Vol. 83, No. 139*: Food and Nutrition Service, USDA.
25. Richardson S (2021) Need to ask Scott about title. *NA*.

26. Searchinger T, Waite R, Hanson C *et al.* (2019) *World Resources report, Creating a sustainable food future, A menu of solutions to feed nearly 10 billion people by 2050*. WRI.
27. Stern A, Blackstone NT, Economos CD *et al.* (2021) Environmental impacts of the United States National School Lunch Program *Communications Earth and Environment*.
28. Heller MC, Willits-Smith A, Mahon T *et al.* (2021) Individual US diets show wide variation in water scarcity footprints. *Nature Food* 2, 255-263.
29. Wernet G, Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. (2016) The ecoinvent database version 3 (part I): overview and methodology. In *The International Journal of Life Cycle Assessment*, vol. 21(9), pp. 1218–1230.
30. USDA and HHS (2020) Dietary Guidelines for Americans, 2020-2025, 9th ed. [USDoAaUSDoHaH Services., editor]. Washington, D.C.
31. Krebs-Smith SM, Pannucci TE, Subar AF *et al.* (2018) Update of the Healthy Eating Index: HEI-2015. *J Acad Nutr Diet* 118, 1591-1602.
32. Kelly Thompson Nutrition Manager at Boston Public Schools (2021) Email Correspondence on Boston Public School Lunches.
33. Stern A, Levine S, Richardson S *et al.* (2021) Designing school lunch menus with minimal environmental impacts using linear programming and optimization. *Journal of Cleaner Production*.
34. Springmann M, Wiebe K, Mason-D'Croz D *et al.* (2018) Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *Lancet Planet Health* 2, e451-e461.
35. (2015) Average Healthy Eating Index-2015 Scores for Americans by Age Group, WWEIA/NHANES 2015-2016 [CDC, editor]: National Center for Health Statistics, What We Eat in America/National Health and Nutrition Examination Survey.
36. Guo X, Warden BA, Paeratakul S *et al.* (2004) Healthy Eating Index and obesity. *Eur J Clin Nutr* 58, 1580-1586.
37. USDA (2014) A Series of Systematic Reviews on the Relationship Between Dietary Patterns and Health Outcomes. Center for Nutrition Policy and Promotion, USDA.

38. Cohen JF, Richardson S, Parker E *et al.* (2014) Impact of the new U.S. Department of Agriculture school meal standards on food selection, consumption, and waste. *Am J Prev Med* 46, 388-394.
39. Schwartz MB, Henderson KE, Read M *et al.* (2015) New school meal regulations increase fruit consumption and do not increase total plate waste. *Child Obes* 11, 242-247.
40. USDA (2019) *School Nutrition and Meal Cost Study: Volume 1 - School Meal Program Operations and School NUtrition Environments (Summary)*. Alexandria, VA: Food and Nutrition Services
41. Aleksandrowicz L, Green R, Joy E *et al.* (2016) The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PLOS ONE* 11.
42. Willett W, Rockström J, Loken B *et al.* (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* 393, 447-492.
43. Wilson N, Cleghorn CL, Cobiac LJ *et al.* (2019) Achieving Healthy and Sustainable Diets: A Review of the Results of Recent Mathematical Optimization Studies. *Adv Nutr* 10, S389-s403.
44. Gazan R, Brouzes CMC, Vieux F *et al.* (2018) Mathematical Optimization to Explore Tomorrow's Sustainable Diets: A Narrative Review. *Advances in Nutrition* 9, 602-616.
45. Kessler HS (2016) Simple interventions to improve healthy eating behaviors in the school cafeteria. *Nutrition reviews* 74 3, 198-20

Chapter 5 : Bringing more sustainable lunches to schools

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Using the National School Lunch Program (NSLP) to Promote Sustainable Diets

For over 70 years, the National School Lunch Program (NSLP) has provided schools with the resources to serve children nutritious and low-cost lunches (FNS 2017). The program reaches tens of millions of children daily and is supported by an annual budget of about 14 billion USD. In 2010, the program was overhauled by the Healthy Hunger Free Kids Act (HHFKA) which updated the nutrition standards, provided wider access to free meals, and promoted local food procurement (PL 111-296, 2010).

While the HHFKA improved many facets of the NSLP, it did not consider the program's environmental impacts (Gearan and Fox 2020, Forrestal et al. 2021). Given the robust evidence linking dietary intake with environmental impacts, further changes to the program could be warranted (Rockström et al. 2020). The global food system is resource intensive and produces nearly a third of all anthropogenic greenhouse gas emissions (Foley et al. 2005, FAO 2012, Tilman et al. 2017, IPBES 2019, Crippa et al. 2021). Managing this resource use and reducing these emissions is critical to ensuring future food security and meeting the targets in the Paris Climate Agreement (Bajželj et al. 2014, Springmann et al. 2018, Willett et al. 2019). To address these issues, research endorses the widespread adoption of sustainable diets, defined as diets

which produce lower environmental impacts, and support health and wellbeing for current and future generations (FAO 2012, Searchinger et al. 2019, Willett et al. 2019).

The NSLP is uniquely suited to promote sustainable diets due to its audience and reach, as well as its adaptiveness and flexibility seen with the recent nutrition standards updates. In the first year after implementation of the new standards, over 80% of schools met the new daily nutrition requirements (USDA 2019). Schools have also embraced the Farm to School grant and training opportunities initiated with the HHFKA. Farm to School connects schools with local food producers and provides activities for students about gardening, cooking, nutrition, and food systems (2010). Most schools have taken advantage of this programming, and in 2019, school food authorities spent over 1 billion USD on local food purchases, which in some cases required the development of new recipes and alterations to menus (FNS 2021). Outside of Farm to School, other interventions, philanthropy, legislation, and resources are driving changes in school lunch menus and reducing student plate waste (Driessen et al. 2014, Kessler 2016, Center for Good Food Purchasing 2017, Metcalfe et al. 2020, National Farm to School Network 2021). This level of commitment suggests that schools are open and able to improve their sourcing and menus.

As for the program's audience and reach, the NSLP serves millions of children daily at a critical time when they are establishing habits for the future. Evidence suggests that peers act as role models for eating behaviors and attitudes towards foods. Given their position, schools have the opportunity to act as mediators of these interactions. Specifically, through activities offered by Farm to School such as taste tests and cooking demonstrations the NSLP is ideally positioned to mediate peer impacts on eating behavior and can help children pursue sustainable eating habits early in life (Houldcroft et al. 2014). Together, this represents a period of transformation and an exceptional atmosphere for the promotion of sustainable diets.

Designing Sustainable Lunch Menus

Before the NSLP can encourage the consumption of sustainable diets, policy makers will need to determine the sustainability of current lunches and consider what changes need to be made to enhance sustainability. Our research estimated the environmental impacts of lunches served

nationally, and then worked directly with a school district to design more sustainable menus by connecting information on environmental impacts with key aspects of sustainable diets including cost, nutritional quality, and student acceptance.

By combining information on the food served in over 1,000 schools with the environmental impacts of producing these foods, we established baseline environmental impact estimates for lunches served in the NSLP. As seen in previous research, meat stood out as a major driver of impacts (Poore and Nemecek 2018, Reinhardt et al. 2020, Heller et al. 2021). Across all impact categories and foods served, meat products contributed the most (28-67% depending on impact category) to total impacts. Compared to the highest impact lunches, the lowest impact lunches contained greater quantities of dairy, whole grains, seafood, and nuts and seeds, which generally aligns with previous research on low-impact diets (Aleksandrowicz et al. 2016, Willett et al. 2019).

To translate these findings into actionable steps for school districts, we partnered with a large urban school district in the Northeastern U.S. to develop sustainable menus. Sustainable menus were designed using foods that the school district currently served and optimization modeling. We first explored designing menus with the lowest environmental impacts, and then incorporated other priorities of the school district including nutritional quality, student consumption, and cost. This modeling study allowed us to explore which lunch menu changes would have the greatest impact on sustainability.

Compared to current menus offered by the district, menus designed with optimization had lower environmental impacts (15-77%) and costs, and greater nutritional quality and student acceptance based on consumption data from previous plate waste studies. Optimized menus offered a mix of poultry, vegetarian, and fish dishes and contained more vegetarian and fish options and less beef and cheese options than current lunches offered. Beef and cheese are commonly offered because they are inexpensive and highly consumed. Even so, we found that removing or reducing beef and cheese from menus can lead to lower costs and potential increases in consumption rates based on previous consumption estimates. However, complete removal of beef or cheese from menus would be a shock for most districts—gradual reductions

would likely be more successful. Advocating these changes might prompt backlash from beef and dairy associations and lobbies which are driving research to demonstrate the environmental benefits of their products (National Cattlemen's Beef Association 2022). However, these findings have been corroborated by a substantial body of literature (Springmann et al. 2018, Searchinger et al. 2019, Willett et al. 2019, Reinhardt et al. 2020).

Despite optimization models selecting vegetarian and fish menu items, these offerings were generally associated with lower consumption. As such, increasing offerings of these items should be approached carefully. Schools could enhance the acceptability of these options by using effective strategies such as marketing campaigns, experiential learning, or other behavior change interventions (Driessen et al. 2014, Kessler 2016, Metcalfe et al. 2020). The groundwork for this introduction is seemingly already underway with fast-food restaurants leading the transition by offering new vegetarian alternatives to standard fare (Kelley 2021).

Implementing Sustainable Lunch Menus

Contextualizing these findings into the larger picture of school lunch programming can help to define actionable steps to make school lunches more sustainable. Here, we explore how these findings can impact policy and funding, school food programming, menu planning, and procurement. While this work focuses on school lunch, this information can also be used when thinking about school breakfast programs.

Nutrition Standards

Before 2010, the nutrition standards for the NSLP had not been updated in 15 years, thus, updating nutrition standards could be an arduous and potentially impractical process which requires buy-in from a wide range of stakeholders (Ralston 2008). This is best illustrated by push back from school food authorities over the implementation of the new nutrition standards. School food authorities expressed concerns over increased plate waste and costs, neither of which have been validated (Schwartz et al. 2015, Buscemi et al. 2018, USDA 2019). Despite these early issues, updating standards has shown to greatly improve the nutritional quality of school lunches and could therefore be an effective mechanism for improving sustainability as well (USDA 2019).

We propose that new standards for lunch planning include minimum requirements for legumes (including peanuts) and fish, and limits for beef and cheese using new sub-groups for meat and meat alternative and new monthly minimum and maximum requirements. Table (1) provides amounts in oz. eq. for the recommended update, based on the current standards and our research findings.

Table 5-1. Recommendations for nutrition standards update to improve the sustainability of school lunches in the U.S.

	Preschool	Grades K-5	Grades 6-8	Grades 9-12
	Amount of Food Per Week (Minimum per day)			
Meat and Meat Alternative (oz. eq.)	7.5 (1.5)	8-10 (1)	9-10 (1)	10-12 (2)
Beans and Peas (Legumes)	1.5	2	2	2
	Amount of Food per Month			
Fish	1.5	4	4	4
Beef	< 4.5	< 6	< 6	< 6
Cheese	< 4.5	< 6	< 6	< 6

We do not present specific recommendations for nuts and seeds, even though there was an association between these foods and lunches with lower environmental impacts. To include recommendations further guidance specifying food types and production practices would be necessary. In general, the impacts of nuts and seeds are relatively low compared to animal-based protein. However, tree nuts, such as almonds and pistachios, require three to six times more water than animal proteins (Mekonnen and Hoekstra 2012, Poore and Nemecek 2018). Lacking a formal recommendation, we encourage the inclusion of alternatives to tree nuts and less commonly served seeds such as sunflower, sesame, or pumpkin seeds on school lunch menus.

While the recommendations for fish will support children's health and were cost effective for the studied district, we have less confidence in this recommendation as it relates to environmental impacts. Threats relevant to fisheries management such as overfishing and biodiversity were not included in this study. Therefore, the fish recommendation is provided with a caveat that fish should be sourced from well-managed, wild populations with fishing methods which reduce by-catch and habitat destruction, this could include small pelagic fish such as herring, sardine, and anchovies (Clark and Tilman 2017, Gephart et al. 2021). Fish such as silver carp and salmon produced in low-intensity, non-recirculating aquaculture could also be good options because they are associated with lower global warming potential than trawling fisheries (Clark and Tilman 2017, Bohnes et al. 2019, Gephart et al. 2021). However, they have relatively high eutrophication potential and can threaten wild species genetics. To reduce the burden for schools in selecting suitable fish options, federal and state agencies and nonprofits could provide lists of acceptable options based on locality.

Funding

Although sustainable menus can have lower costs, many school lunch programs run a deficit, suggesting the need for more funding. The federal government could provide financial incentives for more sustainable lunches such as those currently provided by the states for local food procurement. As of 2020, most states have enacted legislation to enhance school lunch programs (National Farm to School Network 2021). Legislation which provides schools with additional funding varies from budgeting for a Farm to School coordinator and grants programs to additional reimbursements for local food procurement. Michigan and Washington D.C. provide

up to 0.10 USD more for lunches which include locally produced items. Similar funding techniques could be used for sustainable menus if auditing and reimbursements require minimal burden for school districts.

Additional financial support is provided to schools in the form of USDA Foods, also called entitlement foods (FNS 2016). In 2019, USDA Foods added an additional 0.36 USD in value to lunches and accounted for 15 to 20% of food served (FNS 2020). Overall, the value of USDA Foods equals 12% of all federal food assistance provided to schools. There are a wide variety of USDA Foods available, however, red meat and dairy (milk and cheese) account for almost half of the total value provided (45%). Fruits and vegetables represent around one-third of total USDA Foods value, and nuts and seeds, grains, and fish make up less than 3%. With the update to nutrition standards, the federal government made a concerted effort to improve the healthfulness of USDA Foods. New efforts could focus on shifting the types of foods provided by USDA Foods to include more legumes, grains, and seafood. The purpose of USDA Foods is not only to provide financial support to schools but also to strengthen agricultural markets, as such, changing the types of USDA Foods offered presents a unique opportunity to link nutrition and agricultural policy.

In fiscal year 2022, the USDA is providing approximately 12 million USD in grant funding for Farm to School, this is more than double available in previous years. The motives of Farm to School programming align with the promotion of sustainable diets, as such, the funding mechanisms for Farm to School could be used to enhance the sustainability of menus. Farm to School grants allow schools to redesign menus, promote consumption of new menus with interventions like Smarter Lunchroom techniques, and evaluate changes in student acceptance and waste (Mumby et al. 2018, Prescott et al. 2020). Overall Farm to School has been effective at promoting food and nutrition-related knowledge, healthy food selection, nutrition self-efficacy, and willingness to try fruits and vegetables. However, more research is needed to understand impacts on consumption and preferences. Due to the connections between Farm to School and sustainable diets, linking this funding could be an essential resource to support behavior change interventions.

School lunch programming and menu planning

Cafeteria interventions have been successful at improving the consumption of more nutritious foods and could lend to the promotion of sustainable diets (Kessler 2016). Effective interventions have included modifying students' choice, providing incentives for consumption, marketing, and strategies related to time and ease of consumption. For example, to increase fruit and vegetable consumption one school provided children with small rewards (Just and Price 2013). Another study found that students consumed more fruit when it was offered pre-sliced compared to whole (Swanson et al. 2009). Even strategies as simple as changing the names of foods have positively affected student behavior (Kessler 2016). Given the range of effective approaches for improving healthier choices, similar strategies can promote sustainable menus and shift student eating behaviors.

Many school nutrition managers use software for menu planning, and the USDA provides schools with an approved list of nutrient analysis software for use during administrative review. This offers a unique avenue to integrate concepts of sustainability into menu planning. Software could incorporate data on environmental impacts of foods and student consumption to help improve menu planning. This might include weekly limits for menu greenhouse gas emissions or targets for potential consumption rates. While all schools might not have this data available, software could provide this data from national averages. This could also promote partnerships between schools and universities so that specific data related to the district could be integrated. Such a platform could also encourage the sharing of data and knowledge across districts.

These recommendations represent a wide array of steps for governments, schools, non-profits, and private entities to progressively improve the sustainability of the menus offered through the NSLP. If taken, younger generations of Americans will be exposed to more sustainable meals early in life setting the table for a brighter future.

References

The healthy, hunger-free kids act of 2010 (2010) PL 111-296

- Aleksandrowicz, L., R. Green, E. Joy, et al. (2016). "The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: A systematic review." PLOS ONE **11**.
- Bajželj, B., K. S. Richards, J. M. Allwood, et al. (2014). "Importance of food-demand management for climate mitigation." Nature Climate Change **4**(10): 924-929.
- Bohnes, F. A., M. Z. Hauschild, J. Schlundt, et al. (2019). "Life cycle assessments of aquaculture systems: A critical review of reported findings with recommendations for policy and system development." Reviews in Aquaculture **11**(4): 1061-1079.
- Buscemi, J., A. Odoms-Young, A. L. Yaroch, et al. (2018). Position statement: Retain school meal standards and healthy school lunches, Society of Behavioral Medicine.
- Center for Good Food Purchasing. (2017). "Good food purchasing standards 2.0 – september 2017 update." from <https://goodfoodpurchasing.org/good-food-purchasing-standards-update-september-2017/#value-category-updates>.
- Clark, M. and D. Tilman (2017). "Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice." Environmental Research Letters **12**(6): 064016.
- Crippa, M., E. Solazzo, D. Guizzardi, et al. (2021). "Food systems are responsible for a third of global anthropogenic ghg emissions." Nature Food **2**(3): 198-209.
- Driessen, C. E., A. J. Cameron, L. E. Thornton, et al. (2014). "Effect of changes to the school food environment on eating behaviours and/or body weight in children: A systematic review." Obes Rev **15**(12): 968-982.

FAO (2012). Sustainable diets and biodiversity directions and solutions for policy, research and action. Food and Agriculture Organization of the UN. FAO Headquarters, Rome, Nutrition and Consumer Protection Division, FAO: p.7.

FNS (2016). White paper usda foods in the national school lunch program. F. a. N. S. U.S. Department of Agriculture.

FNS (2017). The national school lunch program. USDA. Washington, DC.

FNS (2020). Usda foods in schools/child nutrition usda foods program. USDA, Food and Nutrition Services, United States Department of Agriculture.

FNS (2021). Research summary 2019 farm to school census report (summary). F. a. N. S. U.S. Department of Agriculture.

Foley, J. A., R. DeFries, G. P. Asner, et al. (2005). "Global consequences of land use." Science **309**(5734): 570-574.

Forrestal, S., E. Potamites, J. Guthrie, et al. (2021). "Associations among food security, school meal participation, and students' diet quality in the first school nutrition and meal cost study." Nutrients **13**(2).

Gearan, E. C. and M. K. Fox (2020). "Updated nutrition standards have significantly improved the nutritional quality of school lunches and breakfasts." Journal of the Academy of Nutrition and Dietetics **120**(3): 363-370.

Gephart, J. A., P. J. G. Henriksson, R. W. R. Parker, et al. (2021). "Environmental performance of blue foods." Nature **597**(7876): 360-365.

Heller, M. C., A. Willits-Smith, T. Mahon, et al. (2021). "Individual us diets show wide variation in water scarcity footprints." Nature Food **2**(4): 255-263.

- Houldcroft, L., E. Haycraft and C. Farrow (2014). "Peer and friend influences on children's eating." Social Development **23**(1): 19-40.
- IPBES (2019). Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. J. S. E. S. Brondizio, S. Díaz, and H. T. Ngo. Bonn, Germany, IPBES secretariat.
- Just, D. R. and J. Price (2013). "Using incentives to encourage healthy eating in children." The Journal of Human Resources **48**(4): 855-872.
- Kelley, A. (2021). Beyond meat lands big deals with mcdonald's, kfc, taco bell and pizza hut. The Hill.
- Kessler, H. S. (2016). "Simple interventions to improve healthy eating behaviors in the school cafeteria." Nutrition reviews **74** **3**: 198-209.
- Mekonnen, M. M. and A. Y. Hoekstra (2012). "A global assessment of the water footprint of farm animal products." Ecosystems **15**(3): 401-415.
- Metcalf, J. J., B. Ellison, N. Hamdi, et al. (2020). "A systematic review of school meal nudge interventions to improve youth food behaviors." International Journal of Behavioral Nutrition and Physical Activity **17**(1): 77.
- Mumby, S., M. Leineweber and J. Andrade (2018). "The impact the smarter lunchroom movement strategies have on school children's healthy food selection and consumption: A systematic review." Journal of Child Nutrition & Management **42**(2).
- National Cattlemen's Beef Association. (2022). "Sustainability, commitment to building a sustainable legacy." from <https://www.ncba.org/producers/sustainability#:~:text=Goal%3A%20Demonstrate%20the%20climate%20neutrality,the%20global%20leader%20since%201996>.
- National Farm to School Network (2021). State farm to school policy handbook 2002-2020.

- Poore, J. and T. Nemecek (2018). "Reducing food's environmental impacts through producers and consumers." Science **360**(6392): 987.
- Prescott, M. P., R. Cleary, A. Bonanno, et al. (2020). "Farm to school activities and student outcomes: A systematic review." Advances in Nutrition **11**(2): 357-374.
- Ralston, K., Constance Newman, Annette Clauson, Joanne Guthrie, and Jean Buzby. (2008). The national school lunch program: Background, trends, and issues. E. R. S. U.S. Department of Agriculture.
- Reinhardt, S. L., R. Boehm, N. T. Blackstone, et al. (2020). "Systematic review of dietary patterns and sustainability in the united states." Advances in Nutrition **11**(4): 1016-1031.
- Rockström, J., O. Edenhofer, J. Gaertner, et al. (2020). "Planet-proofing the global food system." Nature Food **1**(1): 3-5.
- Schwartz, M. B., K. E. Henderson, M. Read, et al. (2015). "New school meal regulations increase fruit consumption and do not increase total plate waste." Child Obes **11**(3): 242-247.
- Searchinger, T., R. Waite, C. Hanson, et al. (2019). World resources report, creating a sustainable food future, a menu of solutions to feed nearly 10 billion people by 2050. E. Matthew, WRI.
- Springmann, M., M. Clark, D. Mason-D'Croz, et al. (2018). "Options for keeping the food system within environmental limits." Nature **562**(7728): 519-525.
- Swanson, M., A. Branscum and P. J. Nakayima (2009). "Promoting consumption of fruit in elementary school cafeterias. The effects of slicing apples and oranges." Appetite **53**(2): 264-267.

- Tilman, D., M. Clark, D. R. Williams, et al. (2017). "Future threats to biodiversity and pathways to their prevention." Nature **546**(7656): 73-81.
- USDA (2019). School nutrition and meal cost study: Volume 2 - nutritional characteristics of school meals. School Nutrition and Meal Cost Study. J. Endall, Food and Nutrition Services. **2**.
- USDA (2019). School nutrition and meal cost study: Volume 4 - student participation, satisfaction, plate waste and dietary intakes. School Nutrition and Meal Cost Study. J. Endall, Food and Nutrition Services. **2**.
- Willett, W., J. Rockström, B. Loken, et al. (2019). "Food in the anthropocene: The eat–lancet commission on healthy diets from sustainable food systems." The Lancet **393**(10170): 447-492.

Appendix A: Supplemental Information Aim 1

Hierarchical decision tree

There are 563 commodities in the Food Commodities Intake Database (FCID) and thousands of life cycle inventories (LCI) in ecoinvent 3.6. To appropriately connect commodities in FCID to LCIs in ecoinvent we used a hierarchical decision tree. The tree assessed information for each LCI in the following order to select a single LCI or a proxy group of LCIs for each commodity:

Level 1: Function/Name

This level compared the exact name of the commodity in FCID with the names or functions of LCIs in ecoinvent. When an LCI was not available for an FCID commodity, a similar product or proxy group of LCIs was selected to represent the FCID commodity. Similarity in LCI and FCID commodities were determined based on agricultural production practices, climate for production, and plant botany or animal physiology.

Level 2: Geography

There is a provision in the National School Lunch Program (NSLP) to Buy American which requires school lunch programs to, where feasible, source food produced in the US. LCIs with geographic representation for the US were prioritized, followed by a top importing country, and LCIs with global representation.

Level 3: Consistent LCI Parameters

This level aimed to align LCI parameters such as system boundary, functional unit, and allocation procedures. We used the ecoinvent 3.6 version with allocation cut-off by classification. Functional units were all defined on a mass basis, and system boundaries were to farm gate unless other specified.

Level 4: Temporal Boundary

Finally, LCIs produced with data from the past 20 years or since 2001 were prioritized.

The tree is provided in the accompanying pdf file: SI Figure 1. Hierarchical decision tree

Life cycle inventory selection, proxies, and proxy groups

All LCIs were selected using the hierarchical decision tree. Selections can be found in the accompanying excel file: SI Table 3. Proxy groups and SI Table 4. Life cycle inventory selection for Food Commodities Intake Database Commodities.

Conversions

FCID specifies the form of each commodity for the recipes. For each commodity to be added to a recipe it must first be converted to this form or weight basis. Examples of weight basis include: “Parsnip” weight of roots with or without peel; “Pea, dry” dry weight of pea, “Beef, meat” weight of meat; excluding the weight of bone, and all nutrient fat.

Two conversions were determined for each commodity based on if the commodity was cooked or raw in each recipe. For example, the commodity blueberry could be served cooked if the recipe were for pie but would be served raw if the recipe were for a parfait with raw blueberries on top of yogurt. The raw conversion factor accounts for inedible parts such as pits, cores, or bones and converts to the FCID weight basis. Most conversion factors were derived from the Food Intakes Converted to Retail Commodities Database (FICRCD). Raw conversions were determined by finding the commodity or closest proxy to the commodity in FICRCD. Cooked conversions were determined by finding the commodity or closest proxy to the commodity in a cooked form, not specified as to the cooking methods, with fat not added in cooking.

For converting to the weight basis for animal products, we utilized the same conversion factors for boneless weight for meats and seafood as outlined in Heller et al. (2018) Supplement Table 1.

In FCID fluid milk is divided into three commodities: Milk, fat; Milk, nonfat solids; and Milk, water. To ensure that the impacts of condensed dairy products like cream, cheese, and butter reflected the amount of farm milk required, we allocated the impacts of milk to the milk solids on a dry weight basis and set the impact value of Milk, water to 0. A similar method was utilized in Heller et al. (2018).

Equations for estimating the environmental impacts of lunches

Each menu item in the School Nutrition and Meal Cost study (SNMCS) was represented with a Food and Nutrient Database for Dietary Studies (FNDDS) code. We used these codes and FCID recipes to break down complex food items into agricultural commodities. In the next few paragraphs, we describe FNDDS codes and show how FCID is connected to FNDDS.

What We Eat in America (WWEIA) is a national survey on dietary consumption conducted as part of the National Health and Nutrition Examination Survey . The survey collects two days of dietary intake data from a representative sample of Americans every two years. Using this survey, a database of foods consumed in the US is constructed. The Food and Nutrient Database for Dietary Studies (FNDDS) is made in conjunction with this database. FNDDS is used for processing the food items and nutritional values of the WWEIA intakes. FNDDS includes information necessary for coding individual foods, portion sizes, recipes, and nutrient values of foods. FNDDS is updated with each cycle of WWEIA. There are 8,690 food and beverage items in the most recent cycle of FNDDS and WWEIA.

FNDDS codes, developed for coding individual foods, are an eight-digit number which uniquely identifies a food or beverage. The first number can be one through nine representing nine possible major commodity groups: milk and milk products; meat, poultry, fish and mixtures; dry beans, peas, legumes, nuts, seeds; grain products; fruits; vegetables; fats, oils and salad dressings; sugars, sweets, beverages.

FNDDS can be connected to additional databases to understand the healthfulness of diets and the commodities which make up diets. FNDDS is connected to the Food Patterns Equivalents Database for converting foods to food groups based on the Dietary Guidelines for Americans. This can be used to assess the healthfulness of diets. FNDDS is also connected to FCID and FICRCD to understand the composition of foods by agricultural commodity. For example, the FNDDS food “bread, whole wheat” has the FNDDS code “51300110” and is made up of the following agricultural commodities listed in the table below from FCID. FCID recipes delineate if ingredients are cooked = 2, raw =1, or processed/refined = 9.

SI Table 5. Connection between Food and Nutrient Database for Dietary Studies (FNDDS) and the Food Commodities Intake Database (FCID).

FNDDS Code	FNDDS Description	FCID Code	FCID Description	Commodity proportion	Cooked Status
51300110	bread, whole wheat	1500402000	wheat flour	42.25	9
51300110	bread, whole wheat	1500401000	wheat grain	18.576	2
51300110	bread, whole wheat	1500124000	corn, field, syrup	3.629	2
51300110	bread, whole wheat	600350000	soybean, oil	2.677	2
51300110	bread, whole wheat	1500404000	wheat, bran	1.163	2
51300110	bread, whole wheat	600348000	soybean, flour	0.587	9
51300110	bread, whole wheat	3600223000	milk, nonfat solids	0.561	2
51300110	bread, whole wheat	2003128000	cottonseed, oil	0.233	2
51300110	bread, whole wheat	3600224000	milk, water	0.015	2
51300110	bread, whole wheat	3600222000	milk, fat	0.006	2

The environmental impact per 1 g of each commodity was calculated in openLCA using ReCiPe 2016 Midpoint (H) impact assessment methods. These were multiplied by raw or cooked conversion factors based on the ingredient in the recipe. The converted environmental impact per 1 g of commodity was then multiplied by the grams of each commodity in 100 g of food. This was finally summed across each food recipe to determine the environmental impact of 100 g of each food.

The table below illustrates the math for the average environmental impact estimate for “bread, whole wheat.” In the table, the commodity proportion is the FCID recipe, the GWP kg CO₂ eq/g of commodity is the global warming potential (GWP) of 1 g of a commodity from the database of Food Impacts on the Environment for Linking to Diets from Heller et al. (2018), the GWP CO₂ eq/ 100 g of FNDDS is the GWP kg CO₂ eq/g of commodity multiplied by the commodity proportion, and the total is the sum of the GWP CO₂ eq/ 100 g of FNDDS which equals the GWP per 100 g of bread, whole wheat.

SI Table 6. Calculating the environmental impact for bread, whole wheat.

FNDDS Code	FNDDS Description	FCID Code	FCID Description	Commodity proportion	GWP kg CO₂ eq/g of commodity	GWP CO₂ eq/ 100 g of FNDDS
51300110	bread, whole wheat	1500402000	wheat flour	42.25	3.58E-04	1.51E-02
51300110	bread, whole wheat	1500401000	wheat grain	18.576	3.47E-04	6.45E-03
51300110	bread, whole wheat	1500124000	corn, field, syrup	3.629	7.6E-04	2.76E-03
51300110	bread, whole wheat	600350000	soybean, oil	2.677	8.07E-04	2.16E-03
51300110	bread, whole wheat	1500404000	wheat, bran	1.163	3.58E-04	4.16E-04
51300110	bread, whole wheat	600348000	soybean, flour	0.587	4.06E-04	2.38E-04
51300110	bread, whole wheat	3600223000	milk, nonfat solids	0.561	13.23E-03	7.42E-04
51300110	bread, whole wheat	2003128000	cottonseed, oil	0.233	21.4E-03	4.99E-04
51300110	bread, whole wheat	3600224000	milk, water	0.015	13.23E-03	1.98E-05
51300110	bread, whole wheat	3600222000	milk, fat	0.006	13.23E-03	7.94E-06
Total	bread, whole wheat					2.48E-02/100 g or 0.248 /kg

To calculate the environmental impact of lunches, we multiplied impacts of foods by the total grams served of each food on a given day, then summed impact across foods, and divided by the total number of lunches served that day.

Uncertainty analyses: Validity of environmental data

To confirm the validity of the environmental data, we compared our results for environmental impacts of agricultural commodities to impact results using different impact assessment methods, software, and databases. The following table lists the agricultural commodity impacts we had from combinations of databases, softwares, and impact assessment methods.

SI Table 7. Combinations of databases, softwares, and impact assessment methods for agricultural commodity impact comparison.

Database	Software	Impact Assessment Methods
Ecoinvent 3.6	Online from ecoquery	ILCD 2.0 2018 midpoint no LT
Ecoinvent 3.6	openLCA	ReCipe 2016 Midpoint (H)
World Food LCA Database 3.1	Simapro	ILCD 2011 Midpoint+ V1.06
World Food LCA Database 3.4	Simapro	ILCD 2011 Midpoint+ (April 2016) V1.06 / EU27 2010, equal weighting
World Food LCA Database 3.5	Simapro	PEF

Differences in impact assessment methods, software, and databases make direct comparisons difficult, therefore we ranked and compared the rankings of the nine commodities which accounted for more than 65% of the total mass of food served. Our rankings generally showed alignment across combinations and allowed us to have confidence in our estimates. The results of this comparison are available in the accompanying excel file. This file does not contain the actual impact estimates because this information is proprietary.

Appendix B: Supplemental Information Aim 2

SI Table 1. Cost, nutrient content, and frequency of menu items offered during the 2018-2019 school year.¹

Menu Item Category	Entrée Subcategory 1	Entrée Subcategory 2	Menu Item Name ²	Cost (USD)	Energy (kcal)	Sodium (mg)	Sat. Fat (g)	Frequency Offered ³ (%)
Entrée	Beef	Tomato Salsa	Beef Burrito	0.74	455	610	9.50	1.4
Entrée	Beef	Tomato Salsa	Beef Nachos	0.52	375	595	10.50	1.4
Entrée	Beef	Tomato Salsa	Beef Taco	0.56	435	480	11.00	2.0
Entrée	Beef		Cheeseburger	0.34	301	594	4.50	4.3
Entrée	Beef		Hamburger	0.29	266	489	3.50	6.9
Entrée	Beef		Hot Dog on a Bun with Popcorn	0.99	370	555	6.43	0.5
Entrée	Beef	Cheese	Meatball Pizza	0.74	305	782	5.00	1.3
Entrée	Beef		Meatball Sandwich	0.71	376	724	7.50	2.8
Entrée	Beef		Meatballs and Garlic Bread	0.37	240	410	4.50	0.4
Entrée	Beef		Pepper Jack Cheeseburger	0.71	376	679	9.50	1.3
Entrée	Beef	Pasta	Spaghetti with Marinara and Meatballs	0.91	380	970	7.50	3.9
Entrée	Beef		Steak and Cheese Croissant	0.46	390	810	9.00	1.4
Entrée	Beef		Steak and Cheese Sandwich	1.15	373	692	5.47	1.6
Entrée	Chicken	Barbecue	BBQ Chicken Drumstick with Brown Rice	0.92	300	675	2.15	0.4
Entrée	Chicken	Barbecue	BBQ Chicken Drumstick with Cornbread	1.28	370	765	2.65	0.9
Entrée	Chicken	Barbecue	BBQ Chicken Drumstick with Pesto Pasta	2.83	695	1305	11.65	0.6
Entrée	Chicken	Cheese	BBQ Chicken Pizza	0.74	300	786	4.75	2.4
Entrée	Chicken	Salad	Buffalo Chicken Garden Salad	0.82	231	485	3.75	1.5
Entrée	Chicken	Cheese	Buffalo Chicken Pizza	0.74	290	903	4.75	2.5
Entrée	Chicken	Soy/Orange	Chicken Banh Mi	0.65	323	896	2.44	0.9
Entrée	Chicken	Tomato Salsa	Chicken Burrito	0.86	465	750	8.00	0.5
Entrée	Chicken	Salad	Chicken Caesar Salad	0.87	400	688	7.00	2.1
Entrée	Chicken	Tomato Salsa	Chicken Nachos	0.64	385	735	9.00	1.9
Entrée	Chicken		Chicken Parmesan Sandwich	0.88	286	644	1.50	0.3
Entrée	Chicken	Cheese	Chicken Quesadilla	1.29	380	857	5.79	0.9
Entrée	Chicken	Tomato Salsa	Chicken Taco	0.68	445	620	9.50	0.6

Entrée	Chicken		Chicken Tenders with Cheese Bites	1.20	281	537	2.40	0.8
Entrée	Chicken		Chicken Tenders with Dinner Roll	0.55	284	529	1.40	0.3
Entrée	Chicken		Crispy Chicken Sandwich	0.71	344	679	2.00	2.6
		All						
Entrée	Chicken	Spice/Turmeric	Curry Chicken with Biscuit	0.68	198	656	1.95	0.0
		All						
Entrée	Chicken	Spice/Turmeric	Curry Chicken with Brown Rice	0.57	185	385	1.00	1.0
		All						
Entrée	Chicken	Spice/Turmeric	Curry Chicken with Flatbread	0.70	285	715	2.00	0.0
Entrée	Chicken		Grilled Chicken Sandwich	0.82	284	579	0.50	0.6
		All						
Entrée	Chicken	Spice/Turmeric	Jerk Chicken Drumstick with Brown Rice and Beans	0.89	159	401	2.00	0.8
Entrée	Chicken	Soy/Orange	Mandarin Orange Chicken with Brown Rice	0.77	230	280	0.50	1.5
Entrée	Chicken	Barbecue	Pulled BBQ Chicken Sandwich	0.55	339	862	2.25	0.6
Entrée	Chicken	Barbecue	Pulled BBQ Chicken with Cornbread	0.80	308	593	1.75	0.9
		All						
Entrée	Chicken	Spice/Turmeric	Pulled Jerk Chicken with Biscuit	0.60	190	500	2.05	0.1
		All						
Entrée	Chicken	Spice/Turmeric	Pulled Jerk Chicken with Cornbread	0.85	247	319	1.60	0.0
		All						
Entrée	Chicken	Spice/Turmeric	Seasoned Chicken and Brown Rice	0.40	210	330	2.00	0.4
Entrée	Chicken	Soy/Orange	Teriyaki Chicken with Lo Mein Noodles	0.64	245	590	3.00	1.5
Entrée	Chicken	Soy/Orange	Teriyaki Chicken with Vegetable Fried Rice	0.76	399	504	1.00	1.8
Entrée	Fish		Baked Fish and Cornbread	1.32	410	560	2.50	0.0
Entrée	Fish		Baked Fish in Chip with Brown Rice	0.66	310	260	1.00	1.5
Entrée	Fish		Baked Fish Sandwich	1.07	441	829	3.00	1.6
Entrée	Fish	Tomato Salsa	Fish Burrito	1.12	525	680	7.00	0.1
Entrée	Fish	Tomato Salsa	Fish Taco	0.94	505	550	8.50	0.6
Entrée	Fish	Salad	Garden Salad and Tuna	0.55	147	280	0.98	0.6
Entrée	Fish		Tuna with Pita Bread	0.46	244	460	0.98	0.1
Entrée	Turkey	Salad	Chef Salad with Turkey and Cheese and Pita	1.04	346	850	3.25	2.0
Entrée	Turkey		Roast Turkey with Cornbread and Gravy	1.12	277	812	1.34	0.6
Entrée	Turkey		Turkey and Cheese Sandwich	1.14	267	841	1.50	0.6
Entrée	Vegetarian	Tomato Salsa	Bean Burrito	0.66	459	1048	6.10	3.3

Entrée	Vegetarian	Tomato Salsa	Bean Taco	0.48	439	918	7.60	1.4
Entrée	Vegetarian	Cheese	Broccoli and Cheddar Croissant	0.96	420	870	11.00	1.6
Entrée	Vegetarian	Cheese	Cheese Bites	0.74	70	135	1.00	2.3
Entrée	Vegetarian	Cheese	Cheese Pizza	0.74	270	710	4.50	9.9
Entrée	Vegetarian	Cheese	Cheese Quesadilla	0.97	389	724	10.31	0.8
Entrée	Vegetarian	Cheese	Grilled Cheese	0.37	282	696	4.00	2.5
Entrée	Vegetarian		Hummus, Vegetables, Cheese, and Flatbread	1.27	497	948	7.50	0.4
Entrée	Vegetarian	Cheese	Macaroni and Cheese	0.46	213	412	4.80	1.1
Entrée	Vegetarian	Tofu	Marinated Tofu Banh Mi	0.39	206	444	0.28	0.9
Entrée	Vegetarian	Tofu	Marinated Tofu with Brown Rice	0.28	140	190	0.28	0.3
Entrée	Vegetarian	Tofu	Marinated Tofu with Cornbread	0.64	210	280	0.78	0.0
Entrée	Vegetarian	Tofu	Marinated Tofu with Lo Mein Noodles	0.29	190	450	2.28	1.3
Entrée	Vegetarian	Tofu	Marinated Tofu with Vegetable Fried Rice	0.41	344	364	0.28	0.6
Entrée	Vegetarian	Pasta	Pasta with Pesto	1.99	475	630	9.50	0.0
Entrée	Vegetarian		Peanut Butter and Jelly Sandwich	0.57	300	280	3.00	0.5
Entrée	Vegetarian	Pasta	Spaghetti with Marinara and Cheese	0.72	240	680	3.50	1.5
Entrée	Vegetarian	Cheese	Spinach Quesadilla	1.34	414	804	8.66	0.5
Entrée	Vegetarian		Three Bean Chili with Cornbread	0.72	391	546	7.10	0.3
Entrée	Vegetarian		Three Bean Chili with Tortilla Chips	0.38	381	571	7.60	0.6
Entrée	Vegetarian	Cheese	Toasted Cheese Sandwich and Three Bean Chili	0.45	378	857	3.60	1.1
		All						
Entrée	Vegetarian	Spice/Turmeric	Vegetable Curry with Brown Rice	0.47	333	642	4.76	0.4
Entrée	Vegetarian	Cheese	Veggie Pizza	0.74	267	600	4.39	0.4
Entrée	Vegetarian	Cheese	White Garlic Pizza	0.74	300	650	6.00	3.5
Entrée	Vegetarian		Yogurt Grab and Go	0.81	420	310	1.00	0.3
Fruit			Apple, Fresh	0.23	72	1	0.00	38.0
Fruit			Applesauce	0.23	51	2	0.00	0.1
Fruit			Assorted Chilled Fruit Cups	0.23	61	4	0.00	0.1
Fruit			Banana, Fresh	0.12	105	1	0.00	18.0
Fruit			Blueberries, Frozen	0.25	40	2	0.00	0.1
Fruit			Craisins	0.25	110	0	0.00	0.1
Fruit			Dried Fruit	0.31	120	25	0.00	0.0

Fruit	Mandarin Oranges, Canned	0.22	60	10	0.00	3.5
Fruit	Orange, Medium	0.23	62	0	0.00	21.0
Fruit	Peaches, Canned	0.26	60	5	0.00	1.0
Fruit	Peaches, Fresh	0.70	51	0	0.00	2.2
Fruit	Pear, Fresh	0.25	101	1	0.00	9.0
Fruit	Raisins	0.18	129	4	0.00	0.1
Fruit	Strawberries, Frozen	0.72	25	0	0.00	0.6
Fruit	Strawberry Cups	0.72	90	0	0.00	0.6
Fruit	Strawberry Pouch	0.33	100	70	1.00	0.0
Fruit	Tropical Fruit Blend, Canned	0.27	80	0	0.00	1.0
Fruit	Watermelon, Fresh	0.07	23	1	0.00	4.6
Milk	1% Plain Milk	0.21	110	130	1.50	50.0
Milk	Lactaid Milk, Fat Free	0.46	90	125	0.00	5.8
Milk	Skim Chocolate Milk	0.22	120	180	0.00	43.0
Milk	Skim Plain Milk	0.21	90	130	0.00	7.0
Vegetable	Baked Potato	0.12	139	307	1.14	0.5
Vegetable	Beans, Baked Beans	0.13	119	140	0.90	0.5
Vegetable	Beans, Chickpea Salad	0.13	151	500	0.68	3.0
Vegetable	Beans, Sizzlin' Black Beans	0.12	124	628	0.10	2.9
Vegetable	Broccoli, Raw	0.20	15	14	0.00	1.9
Vegetable	Broccoli, Roasted	0.20	43	33	0.00	5.3
Vegetable	Broccoli, Steamed	0.20	26	22	0.00	2.0
Vegetable	Butternut Squash, Roasted	0.23	92	7	0.00	0.0
Vegetable	Caesar Salad	0.55	270	358	5.00	0.0
Vegetable	Carrots, Baby, Ranch	0.23	65	115	0.00	6.8
Vegetable	Carrots, Roasted	0.08	31	159	0.33	9.8
Vegetable	Cauliflower, Raw	0.10	51	80	0.00	0.0
Vegetable	Cauliflower, Roasted	0.10	27	188	0.33	1.8
Vegetable	Celery Sticks, Ranch	0.20	42	113	0.00	1.6
Vegetable	Cherry Tomatoes, Ranch	0.09	48	60	0.00	1.6
Vegetable	Coleslaw	0.14	47	71	0.44	2.0
Vegetable	Corn on the Cob, 3"	0.20	90	0	0.00	2.9

Vegetable	Corn, Tomato Salsa Street	0.18	161	166	1.40	0.0
Vegetable	Corn, Sweet Kernels	0.08	96	0	0.00	11.6
Vegetable	Cucumber Slices, Ranch	0.12	37	55	0.00	4.5
Vegetable	Diced Potato Hash Browns	0.46	218	221	3.78	0.5
Vegetable	Green Beans, Steamed	0.08	35	0	0.00	0.0
Vegetable	Marinara Cup	0.28	40	200	0.00	0.0
Vegetable	Mashed Potatoes, Recipe 1	0.25	132	394	1.00	0.8
Vegetable	Mashed Potatoes, Recipe 2	0.31	110	340	1.00	0.4
Vegetable	Onions, Cooked	0.04	29	100	0.16	0.1
Vegetable	Parsnips	0.25	75	201	0.35	0.0
Vegetable	Peas	0.08	68	265	0.04	0.4
Vegetable	Peppers, Cooked	0.17	16	86	0.15	0.1
Vegetable	Peppers, Ranch	0.22	42	57	0.03	0.5
Vegetable	Plantain Slices	0.56	300	0	1.00	2.5
Vegetable	Potato Wedges, Seasoned, Ketchup	0.47	130	225	0.50	3.3
Vegetable	Red Potatoes, Roasted	0.10	97	157	0.60	0.0
Vegetable	Romaine, Raw	0.08	5	2	0.00	2.3
Vegetable	Side Salad, Citrus Spinach	0.19	65	73	0.00	2.9
Vegetable	Side Salad, Cucumber and Tomato	0.15	52	51	0.30	1.0
Vegetable	Side Salad, Garden Side	0.19	43	60	0.00	7.6
Vegetable	Side Salad, Kale and Apple	0.17	244	151	0.97	0.0
Vegetable	Spinach, Cooked	0.37	21	248	0.04	0.0
Vegetable	Sweet Potato Wedges	0.31	150	125	2.00	16.0
Vegetable	Turnips, Roasted	0.23	38	76	0.00	0.0
Vegetable	Yuca, Baked	0.47	160	170	1.00	0.5
Vegetable	Yucca Fries, Ketchup	0.51	170	85	1.00	2.8

¹All nutrient content and cost data are per serving.

²Menu items names are summaries of the menu item and do not list all ingredients included. Tacos included cheese, rice, and tomato salsa.

Quesadillas were served with tomato salsa. All salads included ranch dressing, and entrée salads included a side of pita bread. Spaghetti, pasta, fish sandwich, jerk chicken drumstick, pulled BBQ chicken sandwich, and three bean chili are served with cheese. The yogurt grab and go included fruited yogurt, a mozzarella cheese stick, graham cracker sticks and granola.

³Baseline frequencies were assessed over the 2018-2019 school year and are presented as the percent of all items served by menu item category.

SI Table 2. Student Plate Waste Data Imputations.

Subcategory 1	Menu Item	Imputed (Yes = 1, No = 0)	Sample Size Without Imputation	Sample Size with Imputation	Imputation Methods
Beef	Beef Burrito	0	370	NA	NA
Beef	Beef Nachos	0	33	NA	NA
Beef	Beef Taco	0	90	NA	NA
Beef	Cheeseburger	0	463	NA	NA
Beef	Hamburger	1	7	470	Combined Hamburger and Cheeseburger
Beef	Hot Dog on a Bun with Popcorn	0	62	NA	NA
Beef	Meatball Pizza	1	0	130	Used Pepperoni Pizza
Beef	Meatball Sandwich	0	157	NA	NA
Beef	Meatballs and Garlic Bread	0	30	NA	NA
Beef	Pepper Jack Cheeseburger	0	463	NA	NA
Beef	Spaghetti with Marinara and Meatballs	0	477	NA	NA
Beef	Steak and Cheese Croissant	0	32	NA	NA
Beef	Steak and Cheese Sandwich	0	31	NA	NA
Chicken	BBQ Chicken Drumstick with Brown Rice	0	108	NA	NA
Chicken	BBQ Chicken Drumstick with Cornbread	1	0	108	Used BBQ Chicken Drumstick with Brown Rice
Chicken	BBQ Chicken Drumstick with Pesto Pasta	1	0	147	Used Chicken with Pasta, sauce not specified
Chicken	BBQ Chicken Pizza	0	29	NA	NA
Chicken	Buffalo Chicken Garden Salad	1	0	40	Used Chef Salad with Chicken
Chicken	Buffalo Chicken Pizza	1	0	29	Used BBQ Chicken Pizza
Chicken	Chicken Banh Mi	1	0	23	Used Teriyaki Chicken with Vegetable Fried Rice
Chicken	Chicken Burrito	1	0	118	Combined Beef Burrito and Chicken Taco
Chicken	Chicken Caesar Salad	1	0	40	Used Chef Salad with Chicken
Chicken	Chicken Nachos	1	0	33	Used Beef Nachos

Chicken	Chicken Parmesan Sandwich	1	0	62	Used Chicken Melt and Chicken Parmesan with Pasta
Chicken	Chicken Quesadilla	0	224	NA	NA
Chicken	Chicken Taco	1	0	90	Used Beef Taco
Chicken	Chicken Tenders with Cheese Bites	1	0	250	Used Chicken Tenders with Dinner Roll and Cheese Bites
Chicken	Chicken Tenders with Dinner Roll	0	170	NA	NA
Chicken	Crispy Chicken Sandwich	0	206	NA	NA
Chicken	Curry Chicken with Biscuit	1	0	80	Used Curry Chicken with Brown Rice
Chicken	Curry Chicken with Brown Rice	0	80	NA	NA
Chicken	Curry Chicken with Flatbread	1	0	80	Used Curry Chicken with Brown Rice
Chicken	Grilled Chicken Sandwich	0	35	NA	NA
Chicken	Jerk Chicken Drumstick with Brown Rice and Beans	1	0	271	Combined Seasoned Chicken and Brown Rice and Curry Chicken with Brown Rice
Chicken	Mandarin Orange Chicken with Brown Rice	1	11	21	Combined Mandarin Orange Chicken with Brown Rice and General Tso's Chicken
Chicken	Pulled BBQ Chicken Sandwich	0	46	NA	NA
Chicken	Pulled BBQ Chicken with Cornbread	1	0	46	Used Pulled BBQ Chicken Sandwich
Chicken	Pulled Jerk Chicken with Biscuit	1	0	271	Combined Seasoned Chicken and Brown Rice and Curry Chicken with Brown Rice
Chicken	Pulled Jerk Chicken with Cornbread	1	0	271	Combined Seasoned Chicken and Brown Rice and Curry Chicken with Brown Rice
Chicken	Seasoned Chicken and Brown Rice	0	191	NA	NA
Chicken	Teriyaki Chicken with Lo Mein Noodles	0	281	NA	NA
Chicken	Teriyaki Chicken with Vegetable Fried Rice	0	23	NA	NA
Fish	Baked Fish and Cornbread	1	0	75	Used Baked Fish Sandwich
Fish	Baked Fish in Chip with Brown Rice	1	0	75	Used Baked Fish Sandwich
Fish	Baked Fish Sandwich	0	73	NA	NA
Fish	Fish Burrito	1	0	75	Used Baked Fish Sandwich
Fish	Fish Taco	1	0	75	Used Baked Fish Sandwich
Fish	Garden Salad and Tuna	1	0	40	Used Chef Salad with Chicken

Fish	Tuna with Pita Bread	1	0	75	Used Baked Fish Sandwich
Fruit	Apple, Fresh	0	2336	NA	NA
Fruit	Applesauce	1	1	104	Combined Sliced Apples and Applesauce
Fruit	Assorted Chilled Fruit Cups	1	0	20th/80th	80th percentile fruit
Fruit	Banana, Fresh	0	158	NA	NA
Fruit	Blueberries, Frozen	1	0	78	Used Strawberry cups
Fruit	Craisins	1	0	20th/80th	80th percentile fruit
Fruit	Dried Fruit	1	0	20th/80th	80th percentile fruit
Fruit	Mandarin Oranges, Canned	1	0	384	Combined Clementine and Tangerine
Fruit	Orange, Medium	0	930	NA	NA
Fruit	Peaches, Canned	1	0	20th/80th	80th percentile fruit
Fruit	Peaches, Fresh	1	0	283	Used Pear, Fresh
Fruit	Pear, Fresh	0	283	NA	NA
Fruit	Raisins	1	0	20th/80th	80th percentile fruit
Fruit	Strawberries, Frozen	0	83	NA	NA
Fruit	Strawberry Cups	0	83	NA	NA
Fruit	Strawberry Pouch	1	0	20th/80th	80th percentile fruit
Fruit	Tropical Fruit Blend, Canned	1	0	20th/80th	80th percentile fruit
Fruit	Watermelon, Fresh	0	483	NA	NA
Milk	1% Plain Milk	0	2278	NA	NA
Milk	Lactaid Milk, Fat Free	1	13	180	Combined Lactaid Milk and Skim Milk
Milk	Skim Chocolate Milk	0	1271	NA	NA
Milk	Skim Plain Milk	0	167	NA	NA
Turkey	Chef Salad with Turkey and Cheese and Pita	1	0	40	Used Chef Salad with Chicken
Turkey	Roast Turkey with Cornbread and Gravy	1	0	41	Used Turkey and Cheese Sandwich
Turkey	Turkey and Cheese Sandwich	0	41	NA	NA
Vegetable	Baked Potato	1	0	56	Used Potato Wedges
Vegetable	Beans, Baked Beans	0	123	NA	NA
Vegetable	Beans, Chickpea Salad	0	20	NA	NA

Vegetable	Beans, Sizzlin' Black Beans	0	188	NA	NA
Vegetable	Broccoli, Raw	0	36	NA	NA
Vegetable	Broccoli, Roasted	0	139	NA	NA
Vegetable	Broccoli, Steamed	0	645	NA	NA
Vegetable	Butternut Squash, Roasted	1	0	20th/80th	80th percentile vegetable
Vegetable	Caesar Salad	1	0	465	Used Salad Unspecified
Vegetable	Carrots, Baby, Ranch	0	304	NA	NA
Vegetable	Carrots, Roasted	0	348	NA	NA
Vegetable	Cauliflower, Raw	1	0	20th/80th	80th percentile vegetable
Vegetable	Cauliflower, Roasted	1	0	139	Used Broccoli
Vegetable	Celery Sticks, Ranch	0	50	NA	NA
Vegetable	Cherry Tomatoes, Ranch	0	230	NA	NA
Vegetable	Coleslaw	0	39	NA	NA
Vegetable	Corn on the Cob, 3"	0	254	NA	NA
Vegetable	Corn, Mexican Street	0	64	NA	NA
Vegetable	Corn, Sweet Kernels	0	510	NA	NA
Vegetable	Cucumber Slices, Ranch	0	1130	NA	NA
Vegetable	Diced Potato Hash Browns	1	0	56	Combined Potato Wedges and Roasted Potatoes
Vegetable	Green Beans, Steamed	0	66	NA	NA
Vegetable	Marinara Cup	1	0	20th/80th	80th percentile vegetable
Vegetable	Mashed Potatoes, Recipe 1	1	0	576	Combined Potato Wedges and Roasted Potatoes and Sweet Potato Fries
Vegetable	Mashed Potatoes, Recipe 2	1	0	576	Combined Potato Wedges and Roasted Potatoes and Sweet Potato Fries
Vegetable	Onions, Cooked	1	0	20th/80th	80th percentile vegetable
Vegetable	Parsnips	1	0	20th/80th	80th percentile vegetable
Vegetable	Peas	0	290	NA	NA
Vegetable	Peppers, Cooked	1	0	183	Used Peppers, Unspecified if cooked
Vegetable	Peppers, Ranch	0	183	NA	NA
Vegetable	Plantain Slices	1	0	205	Used Yucca Fries

Vegetable	Potato Wedges, Seasoned, Ketchup	0	54	NA	NA
Vegetable	Red Potatoes, Roasted	1	0	56	Combined Potato Wedges and Roasted Potatoes
Vegetable	Romaine, Raw	0	1292	NA	NA
Vegetable	Side Salad, Citrus Spinach	1	4	283	Combined Side Salad and Spinach Salad
Vegetable	Side Salad, Cucumber and Tomato	1	11	290	Combined Tomato and Cucumber Salad and Side Salad
Vegetable	Side Salad, Garden Side	0	279	NA	NA
Vegetable	Side Salad, Kale and Apple	1	0	279	Used Side Salad
Vegetable	Spinach, Cooked	1	0	20th/80th	80th percentile vegetable
Vegetable	Sweet Potato Wedges	0	458	NA	NA
Vegetable	Turnips, Roasted	1	0	20th/80th	80th percentile vegetable
Vegetable	Yuca, Baked	1	0	205	Used Yucca Fries
Vegetable	Yucca Fries, Ketchup	0	205	NA	NA
Vegetarian	Bean Burrito	0	25	NA	NA
Vegetarian	Bean Taco	1	0	188	Combined Black Beans and Black Beans and Corn
Vegetarian	Broccoli and Cheddar Croissant	1	12	64	Combined Broccoli and Cheddar Croissant and Cheese Sandwich
Vegetarian	Cheese Bites	0	20	NA	NA
Vegetarian	Cheese Pizza	0	1781	NA	NA
Vegetarian	Cheese Quesadilla	1	9	233	Combined Cheese Quesadilla and Chicken Quesadilla
Vegetarian	Grilled Cheese	0	52	NA	NA
Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	1	18	20th/80th	20th/80th
Vegetarian	Macaroni and Cheese	0	164	NA	NA
Vegetarian	Marinated Tofu Banh Mi	1	0	20th/80th	80th percentile vegetarian
Vegetarian	Marinated Tofu with Brown Rice	1	0	20th/80th	80th percentile vegetarian
Vegetarian	Marinated Tofu with Cornbread	1	0	20th/80th	80th percentile vegetarian
Vegetarian	Marinated Tofu with Lo Mein Noodles	1	0	20th/80th	80th percentile vegetarian

Vegetarian	Marinated Tofu with Vegetable Fried Rice	1	0	20th/80th	80th percentile vegetarian
Vegetarian	Pasta with Pesto	1	0	32	Used Pasta with Sauce
Vegetarian	Peanut Butter and Jelly Sandwich	0	59	NA	NA
Vegetarian	Spaghetti with Marinara and Cheese	0	32	NA	NA
Vegetarian	Spinach Quesadilla	1	0	233	Combined Cheese Quesadilla and Chicken Quesadilla
Vegetarian	Three Bean Chili with Cornbread	1	0	131	Used Three Bean Salad
Vegetarian	Three Bean Chili with Tortilla Chips	1	0	131	Used Three Bean Salad
Vegetarian	Toasted Cheese Sandwich and Three Bean Chili	1	0	53	Used Cheese Sandwich
Vegetarian	Vegetable Curry with Brown Rice	1	0	80	Used Chicken Curry with Brown Rice
Vegetarian	Veggie Pizza	1	15	1360	Combined Veggie Pizza and Pizza not specified
Vegetarian	White Garlic Pizza	1	0	1781	Combined Cheese Pizza and Pizza not specified
Vegetarian	Yogurt Grab and Go	1	0	20th/80th	80th percentile vegetarian

SI Table 3. Environmental impacts of baseline weekly menus and optimized menus.

Environmental impacts of weekly lunch menus were determined for each optimization model. Models with the least constraints produced the lowest impacts across impact categories. Grey cells are the lowest possible value for a given impact (*g*, *l*, *w*, *m*, *fw*) used in the MIN-DEV model. Blue cells are the lowest possible value for a given impact, subject to repetition constraints, used in the MIN-DEV+REP model.

Weekly Menu Models	GWP kg CO2 eq.	Land Use m2area crop eq.	Water Scarcity Impact m3 water eq.	Eutrophication Marine g N eq.	Freshwater g P eq.	EIS	DEV	Waste (g)
Average of Lunches Offered ¹	9.5	11.6	3.2	19.7	1.2	264	11.1	1291
No Repetition Restrictions								
MIN-GWP	1.7	2.2	1.0	4.9	0.46	197	0.6	1275
MIN-LAND	1.9	2.0	1.2	5.0	0.47	186	1.1	1149
MIN-WATER	2.0	2.2	0.7	5.2	0.54	175	0.8	1229
MIN-MARINE-EU	2.3	2.2	3.4	4.3	0.61	164	4.7	1299
MIN-FRESH-EU	1.8	2.1	1.5	4.8	0.44	190	1.4	1218
MIN-EIS	2.0	2.5	3.9	4.8	0.59	153	5.4	1253
MIN-DEV	1.7	2.1	0.8	4.9	0.49	176	0.4	1235
Repetition Restrictions								
MIN-GWP+REP	2.7	3.1	1.9	6.6	0.75	217	0.4	1288
MIN-LAND+REP	2.8	2.9	2.6	6.8	0.77	209	0.9	1269
MIN-WATER+REP	3.2	3.3	1.5	7.5	0.86	210	0.6	1424
MIN-MARINE-EU+REP	2.8	3.2	3.1	6.5	0.79	211	1.3	1395
MIN-FRESH-EU+REP	2.8	3.1	2.5	6.8	0.72	223	0.8	1424
MIN-EIS+REP	3.1	3.2	3.2	7.3	0.87	194	1.7	1375
MIN-DEV+REP	2.8	3.0	1.8	6.7	0.77	210	0.3	1267
Waste Restrictions								
MIN-DEV+REP+W10	9.4	11.9	3.5	19.6	1.06	251	9.3	999
MIN-DEV+REP+W12	6.1	7.2	2.7	13.2	1.00	235	4.9	1011
MIN-DEV+REP+W20	3.1	3.5	2.1	7.4	0.90	228	1.1	1058

EIS = Environmental Impact Score; DEV = minimized sum of the relative deviation from each of the minimum values.

¹Average across all baseline lunch offerings during the 2018-2019 school year.

SI Table 4. Nutrient content and cost of baseline and optimized menus.

Weekly Menu Models	Mass (g)	Energy (kcal)	Fiber (g)	Sodium (mg)	Saturated Fat (g)	HEI	Cost (USD)
Baseline ¹	3223	3039	44	4749	31	84.4	6.79 ²
No Repetition Restrictions							
MIN-GWP	2782	2796	56	3168	13	99.1	6.70
MIN-LAND	2597	2776	47	3272	13	99.1	6.64
MIN-WATER	2435	2786	62	3123	13	99.3	6.49
MIN-MARINE-EU	2157	2764	47	3517	11	98.1	6.68
MIN-FRESH-EU	2658	2789	48	3657	8	97.7	6.62
MIN-EIS	1978	2771	47	3207	14	98.9	6.69
MIN-DEV	2464	2796	60	3146	14	99.2	6.70
Repetition Restrictions							
MIN-GWP+REP	2959	2861	50	4773	18	93.7	6.69
MIN-LAND+REP	2795	2782	50	4535	18	94.1	6.55
MIN-WATER+REP	2831	2756	55	4670	19	93.4	6.63
MIN-MARINE-EU+REP	2812	2763	47	4566	16	93.9	6.68
MIN-FRESH-EU+REP	3030	2803	45	4640	13	93.8	6.67
MIN-EIS+REP	2523	2884	46	4711	22	94.1	6.67
MIN-DEV+REP	2856	2767	51	4603	18	93.7	6.63
Waste Restrictions							
MIN-DEV+REP+W10	3038	2751	36	4397	24	91.6	6.66
MIN-DEV+REP+W12	3000	2760	34	4527	22	93.8	6.68
MIN-DEV+REP+W20	3063	2770	42	4354	17	94.8	6.67

HEI = Healthy Eating Index, measures the proximity of a diet to the recommendations in the Dietary Guidelines for Americans.

¹Average across all weekly lunch offerings during the 2018-2019 school year.

²The school district strives to maintain the cost of food per lunch below \$1.34, but in some circumstances the school exceeds this amount.

SI Table 5. Weekly menus selected by optimization models with repetition constraints.

Model	Weekday	Entree		Fruit	Vegetable	Milk
		Sub-Cat	Item			
MIN-GWP+REP						
	Monday	Chicken	Teriyaki Chicken with Lo Mein Noodles	Banana, Fresh	Beans, Sizzlin' Black Beans	Skim Chocolate Milk
	Tuesday	Chicken	Crispy Chicken Sandwich	Orange, Fresh	Coleslaw	Skim Chocolate Milk
	Wednesday	Vegetarian	Cheese Bites	Watermelon, Fresh	Corn, Mexican Street	Skim Chocolate Milk
	Thursday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Banana, Fresh	Romaine, Raw	Skim Chocolate Milk
	Friday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Sweet Potato Wedges	Skim Chocolate Milk
MIN-LAND+REP						
	Monday	Chicken	Teriyaki Chicken with Lo Mein Noodles	Banana, Fresh	Beans, Sizzlin' Black Beans	Skim Plain Milk
	Tuesday	Chicken	Crispy Chicken Sandwich	Raisins	Cauliflower, Raw	Skim Plain Milk
	Wednesday	Vegetarian	Cheese Bites	Watermelon, Fresh	Corn, Mexican Street	Skim Plain Milk
	Thursday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Banana, Fresh	Romaine, Raw	Skim Plain Milk
	Friday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Sweet Potato Wedges	Skim Plain Milk
MIN-WATER+REP						
	Monday	Chicken	Curry Chicken with Flatbread	Apple, Fresh	Beans, Chickpea Salad	Skim Plain Milk
	Tuesday	Chicken	Chicken Caesar Salad	Banana, Fresh	Cherry Tomatoes, Ranch	Skim Plain Milk
	Wednesday	Vegetarian	Cheese Bites	Blueberries, Frozen	Green Beans, Steamed	Skim Plain Milk
	Thursday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Banana, Fresh	Romaine, Raw	Skim Plain Milk
	Friday	Fish	Tuna with Pita Bread	Blueberries, Frozen	Peas	Skim Plain Milk
MIN-MARINE-EU+REP						
	Monday	Chicken	Curry Chicken with Brown Rice	Blueberries, Frozen	Beans, Sizzlin' Black Beans	Skim Chocolate Milk
	Tuesday	Chicken	Crispy Chicken Sandwich	Raisins	Coleslaw	Skim Chocolate Milk
	Wednesday	Vegetarian	Cheese Bites	Watermelon, Fresh	Romaine, Raw	Skim Chocolate Milk
	Thursday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Raisins	Sweet Potato Wedges	Skim Chocolate Milk
	Friday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Red Potatoes, Roasted	Skim Chocolate Milk

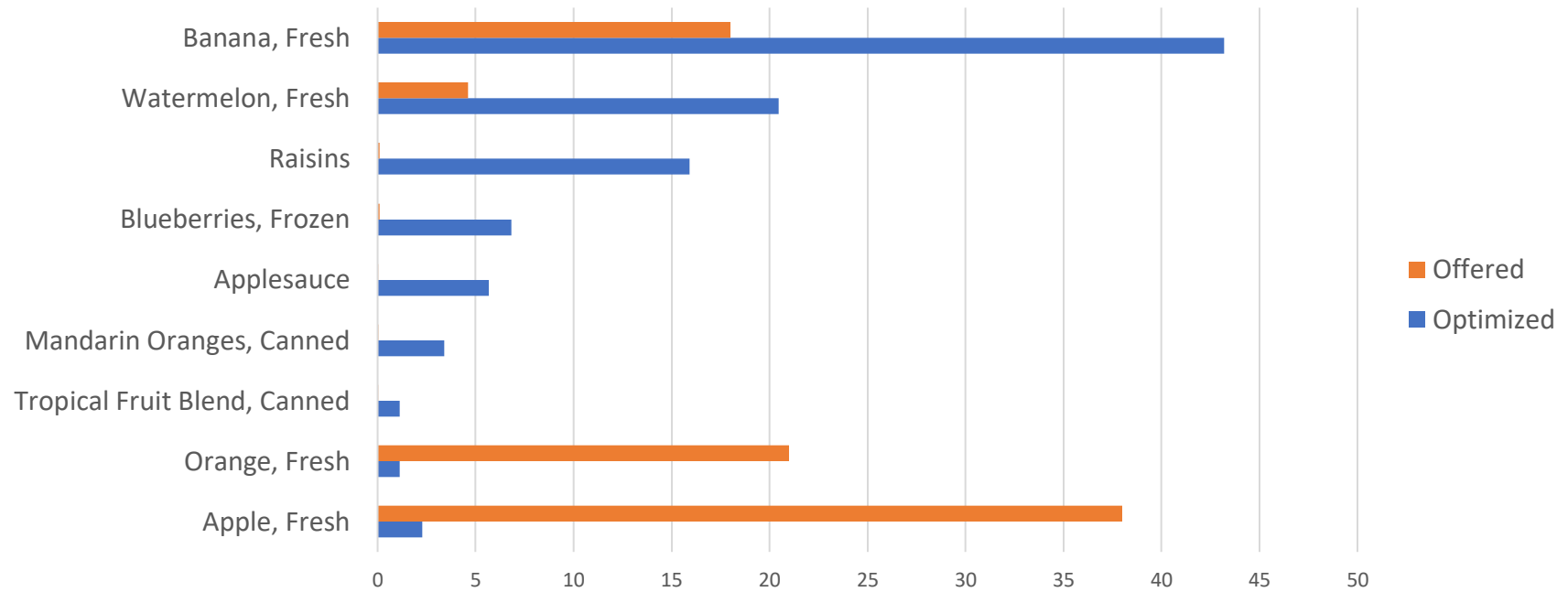
SI Table 5. Weekly menus selected by optimization models with repetition constraints continued.

Model	Weekday	Entree		Fruit	Vegetable	Milk
		Sub-Cat	Item			
MIN-FRESH-EU+REP						
	Monday	Chicken	Teriyaki Chicken with Vegetable Fried Rice	Banana, Fresh	Beans, Sizzlin' Black Beans	Skim Chocolate Milk
	Tuesday	Chicken	Curry Chicken with Flatbread	Tropical Fruit Blend, Canned	Cauliflower, Raw	Skim Chocolate Milk
	Wednesday	Vegetarian	Cheese Bites	Watermelon, Fresh	Marinara Cup	Skim Chocolate Milk
	Thursday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Banana, Fresh	Corn, Sweet Kernels	Skim Chocolate Milk
	Friday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Romaine, Raw	Skim Chocolate Milk
MIN-EIS+REP						
	Monday	Chicken	Curry Chicken with Flatbread	Blueberries, Frozen	Beans, Chickpea Salad	Skim Plain Milk
	Tuesday	Chicken	Chicken Caesar Salad	Raisins	Cauliflower, Raw	Skim Plain Milk
	Wednesday	Vegetarian	Cheese Bites	Watermelon, Fresh	Romaine, Raw	Skim Plain Milk
	Thursday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Raisins	Sweet Potato Wedges	Skim Plain Milk
	Friday	Fish	Tuna with Pita Bread	Watermelon, Fresh	Red Potatoes, Roasted	Skim Plain Milk
MIN-DEV+REP						
	Monday	Chicken	Teriyaki Chicken with Lo Mein Noodles	Banana, Fresh	Beans, Sizzlin' Black Beans	Skim Chocolate Milk
	Tuesday	Chicken	Crispy Chicken Sandwich	Blueberries, Frozen	Corn, Mexican Street	Skim Chocolate Milk
	Wednesday	Vegetarian	Cheese Bites	Watermelon, Fresh	Green Beans, Steamed	Skim Chocolate Milk
	Thursday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Banana, Fresh	Romaine, Raw	Skim Plain Milk
	Friday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Sweet Potato Wedges	Skim Plain Milk

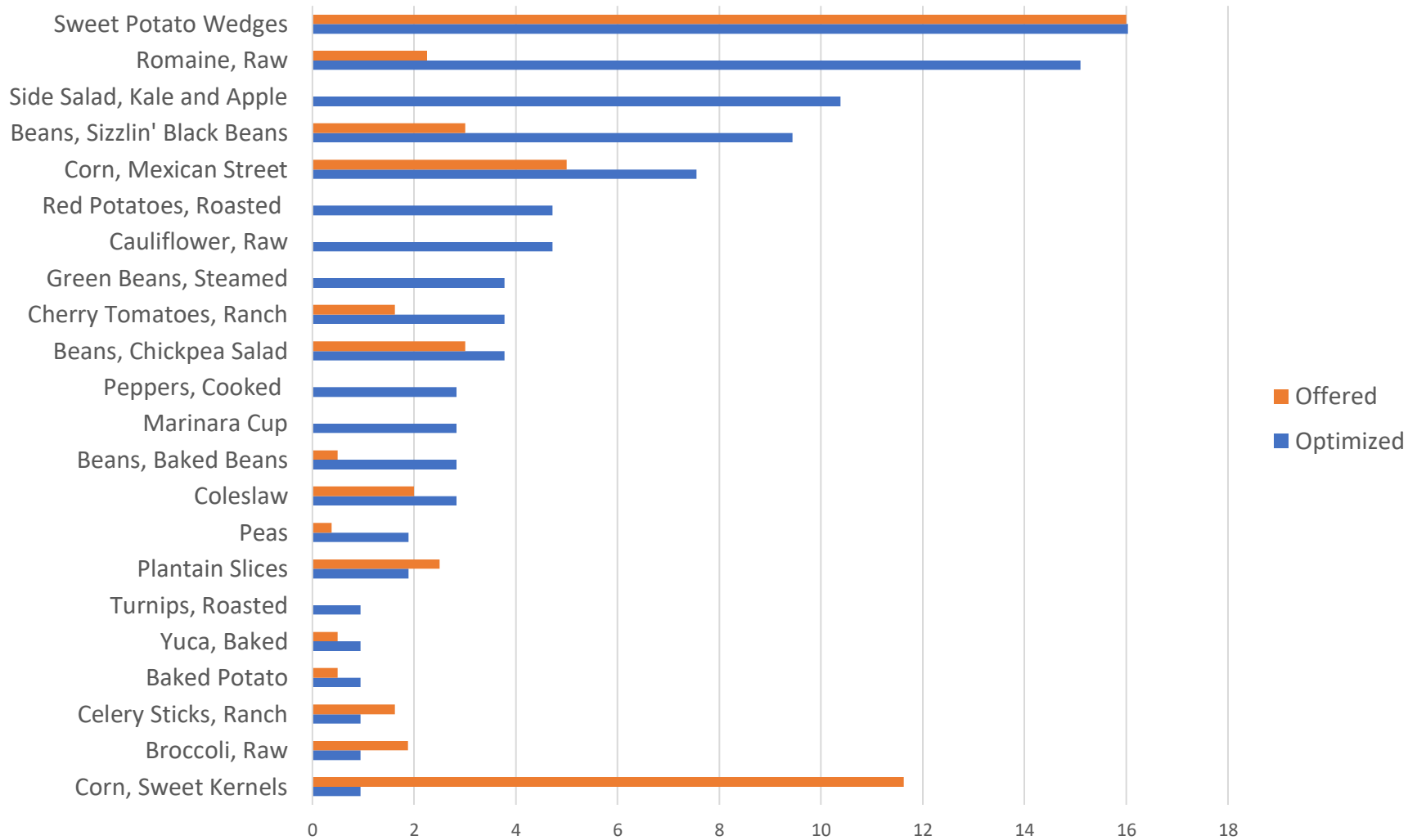
SI Table 5. Weekly menus selected by optimization models with repetition constraints continued.

Model	Weekday	Entree		Fruit	Vegetable	Milk
		Sub-Cat	Item			
MIN-DEV+REP+W10						
	Monday	Vegetarian	Veggie Pizza	Applesauce	Beans, Baked Beans	Skim Chocolate Milk
	Tuesday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Mandarin Oranges, Canned	Broccoli, Raw	Skim Chocolate Milk
	Wednesday	Beef	Hot Dog on a Bun with Popcorn	Watermelon, Fresh	Cherry Tomatoes, Ranch	Skim Chocolate Milk
	Thursday	Beef	Hamburger	Mandarin Oranges, Canned	Red Potatoes, Roasted	Skim Plain Milk
	Friday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Peppers, Cooked	Skim Plain Milk
MIN-DEV+REP+W15						
	Monday	Chicken	Pulled BBQ Chicken with Cornbread	Applesauce	Beans, Baked Beans	Skim Chocolate Milk
	Tuesday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Mandarin Oranges, Canned	Cherry Tomatoes, Ranch	Skim Chocolate Milk
	Wednesday	Vegetarian	Grilled Cheese	Watermelon, Fresh	Romaine, Raw	Skim Plain Milk
	Thursday	Beef	Hot Dog on a Bun with Popcorn	Applesauce	Red Potatoes, Roasted	Skim Plain Milk
	Friday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Peppers, Cooked	Skim Plain Milk
MIN-DEV+REP+W20						
	Monday	Chicken	Pulled BBQ Chicken with Cornbread	Applesauce	Beans, Baked Beans	Skim Chocolate Milk
	Tuesday	Chicken	Crispy Chicken Sandwich	Blueberries, Frozen	Celery Sticks, Ranch	Skim Plain Milk
	Wednesday	Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	Watermelon, Fresh	Cherry Tomatoes, Ranch	Skim Plain Milk
	Thursday	Vegetarian	Peanut Butter and Jelly Sandwich	Applesauce	Romaine, Raw	Skim Plain Milk
	Friday	Fish	Garden Salad and Tuna	Watermelon, Fresh	Baked Potato	Skim Plain Milk

SI Figure 1. Proportion (%) of optimized and baseline menus by fruit.



SI Figure 2. Proportion (%) of optimized and baseline menus by vegetable.



Appendix C: Supplemental Information Aim 3

SI Table 1. Cost, nutrient content, and frequency of menu items offered during the 2018-2019 school year.¹

Menu Item Category	Entrée Subcategory 1	Entrée Subcategory 2	Menu Item Name ²	Cost (USD)	Energy (kcal)	Sodium (mg)	Sat. Fat (g)	Frequency Offered ³ (%)
Entrée	Beef	Tomato Salsa	Beef Burrito	0.74	455	610	9.50	1.4
Entrée	Beef	Tomato Salsa	Beef Nachos	0.52	375	595	10.50	1.4
Entrée	Beef	Tomato Salsa	Beef Taco	0.56	435	480	11.00	2.0
Entrée	Beef		Cheeseburger	0.34	301	594	4.50	4.3
Entrée	Beef		Hamburger	0.29	266	489	3.50	6.9
Entrée	Beef		Hot Dog on a Bun with Popcorn	0.99	370	555	6.43	0.5
Entrée	Beef	Cheese	Meatball Pizza	0.74	305	782	5.00	1.3
Entrée	Beef		Meatball Sandwich	0.71	376	724	7.50	2.8
Entrée	Beef		Meatballs and Garlic Bread	0.37	240	410	4.50	0.4
Entrée	Beef		Pepper Jack Cheeseburger	0.71	376	679	9.50	1.3
Entrée	Beef	Pasta	Spaghetti with Marinara and Meatballs	0.91	380	970	7.50	3.9
Entrée	Beef		Steak and Cheese Croissant	0.46	390	810	9.00	1.4
Entrée	Beef		Steak and Cheese Sandwich	1.15	373	692	5.47	1.6
Entrée	Chicken	Barbecue	BBQ Chicken Drumstick with Brown Rice	0.92	300	675	2.15	0.4
Entrée	Chicken	Barbecue	BBQ Chicken Drumstick with Cornbread	1.28	370	765	2.65	0.9
Entrée	Chicken	Barbecue	BBQ Chicken Drumstick with Pesto Pasta	2.83	695	1305	11.65	0.6
Entrée	Chicken	Cheese	BBQ Chicken Pizza	0.74	300	786	4.75	2.4
Entrée	Chicken	Salad	Buffalo Chicken Garden Salad	0.82	231	485	3.75	1.5
Entrée	Chicken	Cheese	Buffalo Chicken Pizza	0.74	290	903	4.75	2.5
Entrée	Chicken	Soy/Orange	Chicken Banh Mi	0.65	323	896	2.44	0.9
Entrée	Chicken	Tomato Salsa	Chicken Burrito	0.86	465	750	8.00	0.5
Entrée	Chicken	Salad	Chicken Caesar Salad	0.87	400	688	7.00	2.1
Entrée	Chicken	Tomato Salsa	Chicken Nachos	0.64	385	735	9.00	1.9
Entrée	Chicken		Chicken Parmesan Sandwich	0.88	286	644	1.50	0.3
Entrée	Chicken	Cheese	Chicken Quesadilla	1.29	380	857	5.79	0.9

Entrée	Chicken	Tomato Salsa	Chicken Taco	0.68	445	620	9.50	0.6
Entrée	Chicken		Chicken Tenders with Cheese Bites	1.20	281	537	2.40	0.8
Entrée	Chicken		Chicken Tenders with Dinner Roll	0.55	284	529	1.40	0.3
Entrée	Chicken		Crispy Chicken Sandwich	0.71	344	679	2.00	2.6
Entrée	Chicken	All						
Entrée	Chicken	Spice/Turmeric	Curry Chicken with Biscuit	0.68	198	656	1.95	0.0
Entrée	Chicken	All						
Entrée	Chicken	Spice/Turmeric	Curry Chicken with Brown Rice	0.57	185	385	1.00	1.0
Entrée	Chicken	All						
Entrée	Chicken	Spice/Turmeric	Curry Chicken with Flatbread	0.70	285	715	2.00	0.0
Entrée	Chicken		Grilled Chicken Sandwich	0.82	284	579	0.50	0.6
Entrée	Chicken	All	Jerk Chicken Drumstick with Brown Rice and					
Entrée	Chicken	Spice/Turmeric	Beans	0.89	159	401	2.00	0.8
Entrée	Chicken	Soy/Orange	Mandarin Orange Chicken with Brown Rice	0.77	230	280	0.50	1.5
Entrée	Chicken	Barbecue	Pulled BBQ Chicken Sandwich	0.55	339	862	2.25	0.6
Entrée	Chicken	Barbecue	Pulled BBQ Chicken with Cornbread	0.80	308	593	1.75	0.9
Entrée	Chicken	All						
Entrée	Chicken	Spice/Turmeric	Pulled Jerk Chicken with Biscuit	0.60	190	500	2.05	0.1
Entrée	Chicken	All						
Entrée	Chicken	Spice/Turmeric	Pulled Jerk Chicken with Cornbread	0.85	247	319	1.60	0.0
Entrée	Chicken	All						
Entrée	Chicken	Spice/Turmeric	Seasoned Chicken and Brown Rice	0.40	210	330	2.00	0.4
Entrée	Chicken	Soy/Orange	Teriyaki Chicken with Lo Mein Noodles	0.64	245	590	3.00	1.5
Entrée	Chicken	Soy/Orange	Teriyaki Chicken with Vegetable Fried Rice	0.76	399	504	1.00	1.8
Entrée	Fish		Baked Fish and Cornbread	1.32	410	560	2.50	0.0
Entrée	Fish		Baked Fish in Chip with Brown Rice	0.66	310	260	1.00	1.5
Entrée	Fish		Baked Fish Sandwich	1.07	441	829	3.00	1.6
Entrée	Fish	Tomato Salsa	Fish Burrito	1.12	525	680	7.00	0.1
Entrée	Fish	Tomato Salsa	Fish Taco	0.94	505	550	8.50	0.6
Entrée	Fish	Salad	Garden Salad and Tuna	0.55	147	280	0.98	0.6
Entrée	Fish		Tuna with Pita Bread	0.46	244	460	0.98	0.1
Entrée	Turkey	Salad	Chef Salad with Turkey and Cheese and Pita	1.04	346	850	3.25	2.0
Entrée	Turkey		Roast Turkey with Cornbread and Gravy	1.12	277	812	1.34	0.6
Entrée	Turkey		Turkey and Cheese Sandwich	1.14	267	841	1.50	0.6

Entrée	Vegetarian	Tomato Salsa	Bean Burrito	0.66	459	1048	6.10	3.3
Entrée	Vegetarian	Tomato Salsa	Bean Taco	0.48	439	918	7.60	1.4
Entrée	Vegetarian	Cheese	Broccoli and Cheddar Croissant	0.96	420	870	11.00	1.6
Entrée	Vegetarian	Cheese	Cheese Bites	0.74	70	135	1.00	2.3
Entrée	Vegetarian	Cheese	Cheese Pizza	0.74	270	710	4.50	9.9
Entrée	Vegetarian	Cheese	Cheese Quesadilla	0.97	389	724	10.31	0.8
Entrée	Vegetarian	Cheese	Grilled Cheese	0.37	282	696	4.00	2.5
Entrée	Vegetarian		Hummus, Vegetables, Cheese, and Flatbread	1.27	497	948	7.50	0.4
Entrée	Vegetarian	Cheese	Macaroni and Cheese	0.46	213	412	4.80	1.1
Entrée	Vegetarian	Tofu	Marinated Tofu Banh Mi	0.39	206	444	0.28	0.9
Entrée	Vegetarian	Tofu	Marinated Tofu with Brown Rice	0.28	140	190	0.28	0.3
Entrée	Vegetarian	Tofu	Marinated Tofu with Cornbread	0.64	210	280	0.78	0.0
Entrée	Vegetarian	Tofu	Marinated Tofu with Lo Mein Noodles	0.29	190	450	2.28	1.3
Entrée	Vegetarian	Tofu	Marinated Tofu with Vegetable Fried Rice	0.41	344	364	0.28	0.6
Entrée	Vegetarian	Pasta	Pasta with Pesto	1.99	475	630	9.50	0.0
Entrée	Vegetarian		Peanut Butter and Jelly Sandwich	0.57	300	280	3.00	0.5
Entrée	Vegetarian	Pasta	Spaghetti with Marinara and Cheese	0.72	240	680	3.50	1.5
Entrée	Vegetarian	Cheese	Spinach Quesadilla	1.34	414	804	8.66	0.5
Entrée	Vegetarian		Three Bean Chili with Cornbread	0.72	391	546	7.10	0.3
Entrée	Vegetarian		Three Bean Chili with Tortilla Chips	0.38	381	571	7.60	0.6
Entrée	Vegetarian	Cheese	Toasted Cheese Sandwich and Three Bean Chili	0.45	378	857	3.60	1.1
		All						
Entrée	Vegetarian	Spice/Turmeric	Vegetable Curry with Brown Rice	0.47	333	642	4.76	0.4
Entrée	Vegetarian	Cheese	Veggie Pizza	0.74	267	600	4.39	0.4
Entrée	Vegetarian	Cheese	White Garlic Pizza	0.74	300	650	6.00	3.5
Entrée	Vegetarian		Yogurt Grab and Go	0.81	420	310	1.00	0.3
Fruit			Apple, Fresh	0.23	72	1	0.00	38.0
Fruit			Applesauce	0.23	51	2	0.00	0.1
Fruit			Assorted Chilled Fruit Cups	0.23	61	4	0.00	0.1
Fruit			Banana, Fresh	0.12	105	1	0.00	18.0
Fruit			Blueberries, Frozen	0.25	40	2	0.00	0.1
Fruit			Craisins	0.25	110	0	0.00	0.1

Fruit	Dried Fruit	0.31	120	25	0.00	0.0
Fruit	Mandarin Oranges, Canned	0.22	60	10	0.00	3.5
Fruit	Orange, Medium	0.23	62	0	0.00	21.0
Fruit	Peaches, Canned	0.26	60	5	0.00	1.0
Fruit	Peaches, Fresh	0.70	51	0	0.00	2.2
Fruit	Pear, Fresh	0.25	101	1	0.00	9.0
Fruit	Raisins	0.18	129	4	0.00	0.1
Fruit	Strawberries, Frozen	0.72	25	0	0.00	0.6
Fruit	Strawberry Cups	0.72	90	0	0.00	0.6
Fruit	Strawberry Pouch	0.33	100	70	1.00	0.0
Fruit	Tropical Fruit Blend, Canned	0.27	80	0	0.00	1.0
Fruit	Watermelon, Fresh	0.07	23	1	0.00	4.6
Milk	1% Plain Milk	0.21	110	130	1.50	50.0
Milk	Lactaid Milk, Fat Free	0.46	90	125	0.00	5.8
Milk	Skim Chocolate Milk	0.22	120	180	0.00	43.0
Milk	Skim Plain Milk	0.21	90	130	0.00	7.0
Vegetable	Baked Potato	0.12	139	307	1.14	0.5
Vegetable	Beans, Baked Beans	0.13	119	140	0.90	0.5
Vegetable	Beans, Chickpea Salad	0.13	151	500	0.68	3.0
Vegetable	Beans, Sizzlin' Black Beans	0.12	124	628	0.10	2.9
Vegetable	Broccoli, Raw	0.20	15	14	0.00	1.9
Vegetable	Broccoli, Roasted	0.20	43	33	0.00	5.3
Vegetable	Broccoli, Steamed	0.20	26	22	0.00	2.0
Vegetable	Butternut Squash, Roasted	0.23	92	7	0.00	0.0
Vegetable	Caesar Salad	0.55	270	358	5.00	0.0
Vegetable	Carrots, Baby, Ranch	0.23	65	115	0.00	6.8
Vegetable	Carrots, Roasted	0.08	31	159	0.33	9.8
Vegetable	Cauliflower, Raw	0.10	51	80	0.00	0.0
Vegetable	Cauliflower, Roasted	0.10	27	188	0.33	1.8
Vegetable	Celery Sticks, Ranch	0.20	42	113	0.00	1.6
Vegetable	Cherry Tomatoes, Ranch	0.09	48	60	0.00	1.6
Vegetable	Coleslaw	0.14	47	71	0.44	2.0

Vegetable	Corn on the Cob, 3"	0.20	90	0	0.00	2.9
Vegetable	Corn, Tomato Salsa Street	0.18	161	166	1.40	0.0
Vegetable	Corn, Sweet Kernels	0.08	96	0	0.00	11.6
Vegetable	Cucumber Slices, Ranch	0.12	37	55	0.00	4.5
Vegetable	Diced Potato Hash Browns	0.46	218	221	3.78	0.5
Vegetable	Green Beans, Steamed	0.08	35	0	0.00	0.0
Vegetable	Marinara Cup	0.28	40	200	0.00	0.0
Vegetable	Mashed Potatoes, Recipe 1	0.25	132	394	1.00	0.8
Vegetable	Mashed Potatoes, Recipe 2	0.31	110	340	1.00	0.4
Vegetable	Onions, Cooked	0.04	29	100	0.16	0.1
Vegetable	Parsnips	0.25	75	201	0.35	0.0
Vegetable	Peas	0.08	68	265	0.04	0.4
Vegetable	Peppers, Cooked	0.17	16	86	0.15	0.1
Vegetable	Peppers, Ranch	0.22	42	57	0.03	0.5
Vegetable	Plantain Slices	0.56	300	0	1.00	2.5
Vegetable	Potato Wedges, Seasoned, Ketchup	0.47	130	225	0.50	3.3
Vegetable	Red Potatoes, Roasted	0.10	97	157	0.60	0.0
Vegetable	Romaine, Raw	0.08	5	2	0.00	2.3
Vegetable	Side Salad, Citrus Spinach	0.19	65	73	0.00	2.9
Vegetable	Side Salad, Cucumber and Tomato	0.15	52	51	0.30	1.0
Vegetable	Side Salad, Garden Side	0.19	43	60	0.00	7.6
Vegetable	Side Salad, Kale and Apple	0.17	244	151	0.97	0.0
Vegetable	Spinach, Cooked	0.37	21	248	0.04	0.0
Vegetable	Sweet Potato Wedges	0.31	150	125	2.00	16.0
Vegetable	Turnips, Roasted	0.23	38	76	0.00	0.0
Vegetable	Yuca, Baked	0.47	160	170	1.00	0.5
Vegetable	Yucca Fries, Ketchup	0.51	170	85	1.00	2.8

¹All nutrient content and cost data are per serving.

²Menu items names are summaries of the menu item and do not list all ingredients included. Tacos included cheese, rice, and tomato salsa.

Quesadillas were served with tomato salsa. All salads included ranch dressing, and entrée salads included a side of pita bread. Spaghetti, pasta, fish sandwich, jerk chicken drumstick, pulled BBQ chicken sandwich, and three bean chili are served with cheese. The yogurt grab and go included fruited yogurt, a mozzarella cheese stick, graham cracker sticks and granola.

³Baseline frequencies were assessed over the 2018-2019 school year and are presented as the percent of all items served by menu item category.

SI Table 2. Student Plate Waste Data Imputations.

Subcategory 1	Menu Item	Imputed (Yes = 1, No = 0)	Sample Size Without Imputation	Sample Size with Imputation	Imputation Methods
Beef	Beef Burrito	0	370	NA	NA
Beef	Beef Nachos	0	33	NA	NA
Beef	Beef Taco	0	90	NA	NA
Beef	Cheeseburger	0	463	NA	NA
Beef	Hamburger	1	7	470	Combined Hamburger and Cheeseburger
Beef	Hot Dog on a Bun with Popcorn	0	62	NA	NA
Beef	Meatball Pizza	1	0	130	Used Pepperoni Pizza
Beef	Meatball Sandwich	0	157	NA	NA
Beef	Meatballs and Garlic Bread	0	30	NA	NA
Beef	Pepper Jack Cheeseburger	0	463	NA	NA
Beef	Spaghetti with Marinara and Meatballs	0	477	NA	NA
Beef	Steak and Cheese Croissant	0	32	NA	NA
Beef	Steak and Cheese Sandwich	0	31	NA	NA
Chicken	BBQ Chicken Drumstick with Brown Rice	0	108	NA	NA
Chicken	BBQ Chicken Drumstick with Cornbread	1	0	108	Used BBQ Chicken Drumstick with Brown Rice
Chicken	BBQ Chicken Drumstick with Pesto Pasta	1	0	147	Used Chicken with Pasta, sauce not specified
Chicken	BBQ Chicken Pizza	0	29	NA	NA
Chicken	Buffalo Chicken Garden Salad	1	0	40	Used Chef Salad with Chicken
Chicken	Buffalo Chicken Pizza	1	0	29	Used BBQ Chicken Pizza
Chicken	Chicken Banh Mi	1	0	23	Used Teriyaki Chicken with Vegetable Fried Rice
Chicken	Chicken Burrito	1	0	118	Combined Beef Burrito and Chicken Taco

Chicken	Chicken Caesar Salad	1	0	40	Used Chef Salad with Chicken
Chicken	Chicken Nachos	1	0	33	Used Beef Nachos
Chicken	Chicken Parmesan Sandwich	1	0	62	Used Chicken Melt and Chicken Parmesan with Pasta
Chicken	Chicken Quesadilla	0	224	NA	NA
Chicken	Chicken Taco	1	0	90	Used Beef Taco
Chicken	Chicken Tenders with Cheese Bites	1	0	250	Used Chicken Tenders with Dinner Roll and Cheese Bites
Chicken	Chicken Tenders with Dinner Roll	0	170	NA	NA
Chicken	Crispy Chicken Sandwich	0	206	NA	NA
Chicken	Curry Chicken with Biscuit	1	0	80	Used Curry Chicken with Brown Rice
Chicken	Curry Chicken with Brown Rice	0	80	NA	NA
Chicken	Curry Chicken with Flatbread	1	0	80	Used Curry Chicken with Brown Rice
Chicken	Grilled Chicken Sandwich	0	35	NA	NA
Chicken	Jerk Chicken Drumstick with Brown Rice and Beans	1	0	271	Combined Seasoned Chicken and Brown Rice and Curry Chicken with Brown Rice
Chicken	Mandarin Orange Chicken with Brown Rice	1	11	21	Combined Mandarin Orange Chicken with Brown Rice and General Tso's Chicken
Chicken	Pulled BBQ Chicken Sandwich	0	46	NA	NA
Chicken	Pulled BBQ Chicken with Cornbread	1	0	46	Used Pulled BBQ Chicken Sandwich
Chicken	Pulled Jerk Chicken with Biscuit	1	0	271	Combined Seasoned Chicken and Brown Rice and Curry Chicken with Brown Rice
Chicken	Pulled Jerk Chicken with Cornbread	1	0	271	Combined Seasoned Chicken and Brown Rice and Curry Chicken with Brown Rice
Chicken	Seasoned Chicken and Brown Rice	0	191	NA	NA
Chicken	Teriyaki Chicken with Lo Mein Noodles	0	281	NA	NA
Chicken	Teriyaki Chicken with Vegetable Fried Rice	0	23	NA	NA
Fish	Baked Fish and Cornbread	1	0	75	Used Baked Fish Sandwich
Fish	Baked Fish in Chip with Brown Rice	1	0	75	Used Baked Fish Sandwich
Fish	Baked Fish Sandwich	0	73	NA	NA
Fish	Fish Burrito	1	0	75	Used Baked Fish Sandwich

Fish	Fish Taco	1	0	75	Used Baked Fish Sandwich
Fish	Garden Salad and Tuna	1	0	40	Used Chef Salad with Chicken
Fish	Tuna with Pita Bread	1	0	75	Used Baked Fish Sandwich
Fruit	Apple, Fresh	0	2336	NA	NA
Fruit	Applesauce	1	1	104	Combined Sliced Apples and Applesauce
Fruit	Assorted Chilled Fruit Cups	1	0	20th	20th percentile fruit
Fruit	Banana, Fresh	0	158	NA	NA
Fruit	Blueberries, Frozen	1	0	78	Used Strawberry cups
Fruit	Craisins	1	0	20th	20th percentile fruit
Fruit	Dried Fruit	1	0	20th	20th percentile fruit
Fruit	Mandarin Oranges, Canned	1	0	384	Combined Clementine and Tangerine
Fruit	Orange, Medium	0	930	NA	NA
Fruit	Peaches, Canned	1	0	20th	20th percentile fruit
Fruit	Peaches, Fresh	1	0	283	Used Pear, Fresh
Fruit	Pear, Fresh	0	283	NA	NA
Fruit	Raisins	1	0	20th	20th percentile fruit
Fruit	Strawberries, Frozen	0	83	NA	NA
Fruit	Strawberry Cups	0	83	NA	NA
Fruit	Strawberry Pouch	1	0	20th	20th percentile fruit
Fruit	Tropical Fruit Blend, Canned	1	0	20th	20th percentile fruit
Fruit	Watermelon, Fresh	0	483	NA	NA
Milk	1% Plain Milk	0	2278	NA	NA
Milk	Lactaid Milk, Fat Free	1	13	180	Combined Lactaid Milk and Skim Milk
Milk	Skim Chocolate Milk	0	1271	NA	NA
Milk	Skim Plain Milk	0	167	NA	NA
Turkey	Chef Salad with Turkey and Cheese and Pita	1	0	40	Used Chef Salad with Chicken
Turkey	Roast Turkey with Cornbread and Gravy	1	0	41	Used Turkey and Cheese Sandwich
Turkey	Turkey and Cheese Sandwich	0	41	NA	NA
Vegetable	Baked Potato	1	0	56	Used Potato Wedges

Vegetable	Beans, Baked Beans	0	123	NA	NA
Vegetable	Beans, Chickpea Salad	0	20	NA	NA
Vegetable	Beans, Sizzlin' Black Beans	0	188	NA	NA
Vegetable	Broccoli, Raw	0	36	NA	NA
Vegetable	Broccoli, Roasted	0	139	NA	NA
Vegetable	Broccoli, Steamed	0	645	NA	NA
Vegetable	Butternut Squash, Roasted	1	0	20th	20th percentile vegetable
Vegetable	Caesar Salad	1	0	465	Used Salad Unspecified
Vegetable	Carrots, Baby, Ranch	0	304	NA	NA
Vegetable	Carrots, Roasted	0	348	NA	NA
Vegetable	Cauliflower, Raw	1	0	20th	20th percentile vegetable
Vegetable	Cauliflower, Roasted	1	0	139	Used Broccoli
Vegetable	Celery Sticks, Ranch	0	50	NA	NA
Vegetable	Cherry Tomatoes, Ranch	0	230	NA	NA
Vegetable	Coleslaw	0	39	NA	NA
Vegetable	Corn on the Cob, 3"	0	254	NA	NA
Vegetable	Corn, Mexican Street	0	64	NA	NA
Vegetable	Corn, Sweet Kernels	0	510	NA	NA
Vegetable	Cucumber Slices, Ranch	0	1130	NA	NA
Vegetable	Diced Potato Hash Browns	1	0	56	Combined Potato Wedges and Roasted Potatoes
Vegetable	Green Beans, Steamed	0	66	NA	NA
Vegetable	Marinara Cup	1	0	20th	20th percentile vegetable
Vegetable	Mashed Potatoes, Recipe 1	1	0	576	Combined Potato Wedges and Roasted Potatoes and Sweet Potato Fries
Vegetable	Mashed Potatoes, Recipe 2	1	0	576	Combined Potato Wedges and Roasted Potatoes and Sweet Potato Fries
Vegetable	Onions, Cooked	1	0	20th	20th percentile vegetable
Vegetable	Parsnips	1	0	20th	20th percentile vegetable
Vegetable	Peas	0	290	NA	NA
Vegetable	Peppers, Cooked	1	0	183	Used Peppers, Unspecified if cooked

Vegetable	Peppers, Ranch	0	183	NA	NA
Vegetable	Plantain Slices	1	0	205	Used Yucca Fries
Vegetable	Potato Wedges, Seasoned, Ketchup	0	54	NA	NA
Vegetable	Red Potatoes, Roasted	1	0	56	Combined Potato Wedges and Roasted Potatoes
Vegetable	Romaine, Raw	0	1292	NA	NA
Vegetable	Side Salad, Citrus Spinach	1	4	283	Combined Side Salad and Spinach Salad
Vegetable	Side Salad, Cucumber and Tomato	1	11	290	Combined Tomato and Cucumber Salad and Side Salad
Vegetable	Side Salad, Garden Side	0	279	NA	NA
Vegetable	Side Salad, Kale and Apple	1	0	279	Used Side Salad
Vegetable	Spinach, Cooked	1	0	20th	20th percentile vegetable
Vegetable	Sweet Potato Wedges	0	458	NA	NA
Vegetable	Turnips, Roasted	1	0	20th	20th percentile vegetable
Vegetable	Yuca, Baked	1	0	205	Used Yucca Fries
Vegetable	Yucca Fries, Ketchup	0	205	NA	NA
Vegetarian	Bean Burrito	0	25	NA	NA
Vegetarian	Bean Taco	1	0	188	Combined Black Beans and Black Beans and Corn
Vegetarian	Broccoli and Cheddar Croissant	1	12	64	Combined Broccoli and Cheddar Croissant and Cheese Sandwich
Vegetarian	Cheese Bites	0	20	NA	NA
Vegetarian	Cheese Pizza	0	1781	NA	NA
Vegetarian	Cheese Quesadilla	1	9	233	Combined Cheese Quesadilla and Chicken Quesadilla
Vegetarian	Grilled Cheese	0	52	NA	NA
Vegetarian	Hummus, Vegetables, Cheese, and Flatbread	1	18	20th	20th
Vegetarian	Macaroni and Cheese	0	164	NA	NA
Vegetarian	Marinated Tofu Banh Mi	1	0	20th	20th percentile vegetarian
Vegetarian	Marinated Tofu with Brown Rice	1	0	20th	20th percentile vegetarian
Vegetarian	Marinated Tofu with Cornbread	1	0	20th	20th percentile vegetarian

Vegetarian	Marinated Tofu with Lo Mein Noodles	1	0	20th	20th percentile vegetarian
Vegetarian	Marinated Tofu with Vegetable Fried Rice	1	0	20th	20th percentile vegetarian
Vegetarian	Pasta with Pesto	1	0	32	Used Pasta with Sauce
Vegetarian	Peanut Butter and Jelly Sandwich	0	59	NA	NA
Vegetarian	Spaghetti with Marinara and Cheese	0	32	NA	NA
Vegetarian	Spinach Quesadilla	1	0	233	Combined Cheese Quesadilla and Chicken Quesadilla
Vegetarian	Three Bean Chili with Cornbread	1	0	131	Used Three Bean Salad
Vegetarian	Three Bean Chili with Tortilla Chips	1	0	131	Used Three Bean Salad
Vegetarian	Toasted Cheese Sandwich and Three Bean Chili	1	0	53	Used Cheese Sandwich
Vegetarian	Vegetable Curry with Brown Rice	1	0	80	Used Chicken Curry with Brown Rice
Vegetarian	Veggie Pizza	1	15	1360	Combined Veggie Pizza and Pizza not specified
Vegetarian	White Garlic Pizza	1	0	1781	Combined Cheese Pizza and Pizza not specified
Vegetarian	Yogurt Grab and Go	1	0	20th	20th percentile vegetarian

SI Table 3. Weekly menus selected by optimization models.

Model	Weekday	Entree Sub-Cat	Item	Fruit	Vegetable	Milk
MAX-CALCON						
	Monday	Beef	Meatball Pizza	Applesauce	Baked Potato and Cauliflower, Roasted	Skim Chocolate Milk
	Tuesday	Chicken	Pulled BBQ Chicken Sandwich	Mandarin Oranges, Canned	Beans, Baked Beans	Skim Chocolate Milk
	Wednesday	Vegetarian	Peanut Butter and Jelly Sandwich	Mandarin Oranges, Canned	Cherry Tomatoes, Ranch and Romaine, Raw	Skim Plain Milk
	Thursday	Chicken	Chicken Tenders with Dinner Roll	Watermelon, Fresh	Baked Potato and Cherry Tomatoes, Ranch	Skim Plain Milk
	Friday	Beef	Hot Dog on a Bun with Popcorn	Watermelon, Fresh	Plantain Slices and Red Potatoes, Roasted	Skim Plain Milk
MAX-COSTCON						
	Monday	Beef	Hamburger	Blueberries, Frozen	Beans, Baked Beans and Red Potatoes, Roasted	Skim Plain Milk
	Tuesday	Chicken	Chicken Tenders with Dinner Roll	Mandarin Oranges, Canned	Cherry Tomatoes, Ranch	Skim Plain Milk
	Wednesday	Vegetarian	Veggie Pizza	Watermelon, Fresh	Cucumber Slices, Ranch and Red Potatoes, Roasted	Skim Plain Milk
	Thursday	Chicken	Pulled BBQ Chicken with Cornbread	Blueberries, Frozen	Plantain Slices	Skim Plain Milk
	Friday	Beef	Hot Dog on a Bun with Popcorn	Mandarin Oranges, Canned	Romaine, Raw and Cherry Tomatoes, Ranch	Skim Plain Milk
MIN-COST						
	Monday	Beef	Hamburger	Banana, Fresh	Beans, Sizzlin' Black Beans	1% Plain Milk
	Tuesday	Vegetarian	Three Bean Chili with Tortilla Chips	Raisins	x2 Carrots, Roasted	1% Plain Milk
	Wednesday	Chicken	Seasoned Chicken and Brown Rice	Watermelon, Fresh	Corn, Sweet Kernels and Peas	Skim Plain Milk
	Thursday	Vegetarian	Grilled Cheese	Banana, Fresh	x2 Green Beans, Steamed	Skim Plain Milk
	Friday	Beef	Steak and Cheese Croissant	Watermelon, Fresh	Romaine, Raw	Skim Plain Milk

x2 = two servings of the vegetable

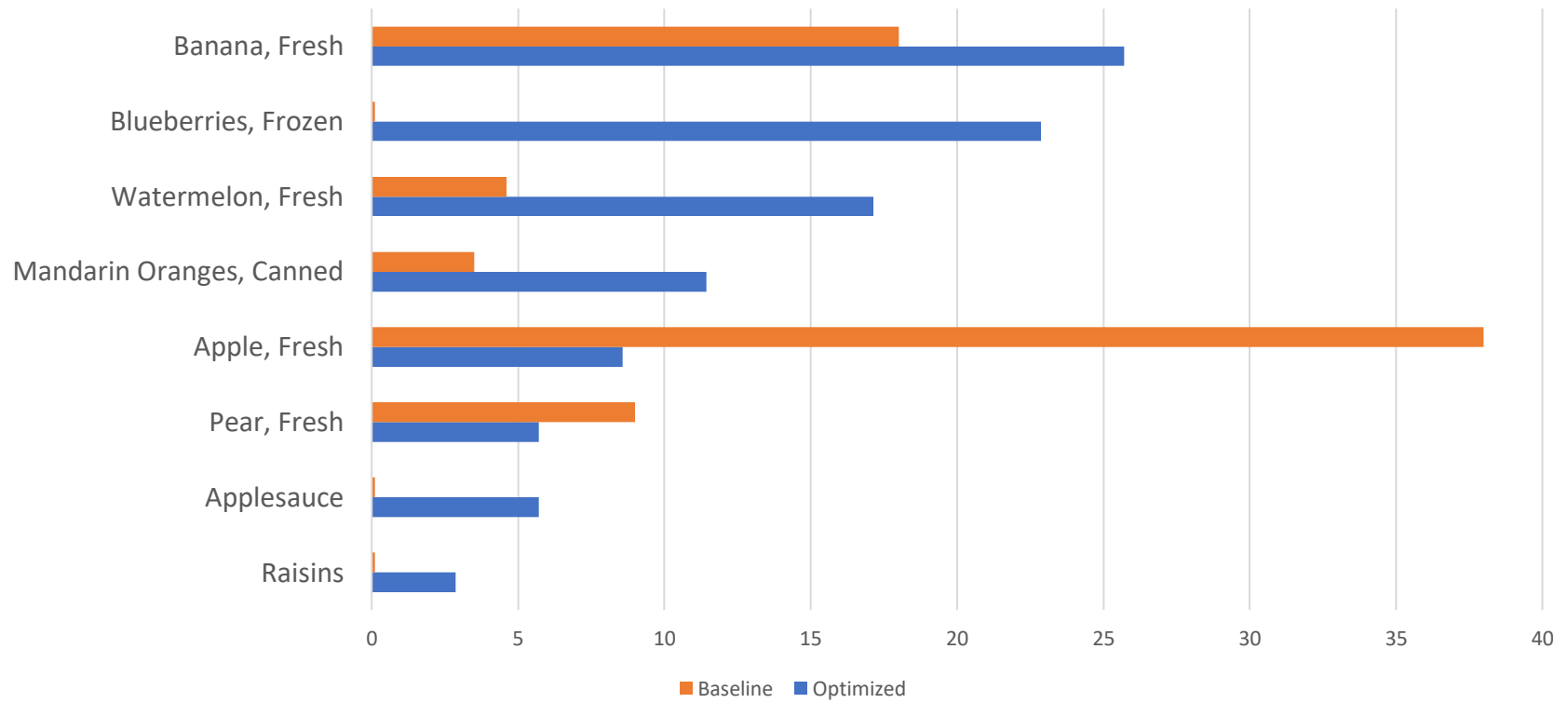
SI Table 3 Cont. Weekly menus selected by optimization models.

Model	Weekday	Entree		Fruit	Vegetable	Milk
		Sub-Cat	Item			
CON-COST-HEI-ENV						
	Monday	Chicken	Curry Chicken with Flatbread	Apple, Fresh	Beans, Chickpea Salad	Skim Plain Milk
	Tuesday	Chicken	Chicken Tenders with Dinner Roll	Banana, Fresh	Romaine, Raw and Sweet Potato Wedges	Skim Plain Milk
	Wednesday	Vegetarian	Cheese Bites	Blueberries, Frozen	Red Potatoes, Roasted and Green Beans, Steamed	Skim Plain Milk
	Thursday	Vegetarian	Marinated Tofu with Vegetable Fried Rice	Banana, Fresh	Side Salad, Kale and Apple	Skim Plain Milk
	Friday	Fish	Tuna with Pita Bread	Blueberries, Frozen	Romaine, Raw and Cherry Tomatoes, Ranch	Skim Plain Milk
CON10-COST-HEI-ENV						
	Monday	Chicken	Crispy Chicken Sandwich	Applesauce	Plantain Slices and Side Salad, Kale and Apple	Skim Plain Milk
	Tuesday	Chicken	Chicken Tenders with Dinner Roll	Banana, Fresh	Romaine, Raw and Cherry Tomatoes, Ranch	Skim Plain Milk
	Wednesday	Vegetarian	Cheese Bites	Blueberries, Frozen	Green Beans, Steamed	Skim Plain Milk
	Thursday	Vegetarian	Marinated Tofu with Brown Rice	Banana, Fresh	Plantain Slices and Side Salad, Kale and Apple	Skim Plain Milk
	Friday	Fish	Tuna with Pita Bread	Blueberries, Frozen	Beans, Chickpea Salad and Cherry Tomatoes, Ranch	Skim Plain Milk
CON30-COST-HEI-ENV						
	Monday	Vegetarian	White Garlic Pizza	Banana, Fresh	Romaine, Raw and Cherry Tomatoes, Ranch	Skim Plain Milk
	Tuesday	Chicken	Chicken Tenders with Dinner Roll	Blueberries, Frozen	Beans, Sizzlin' Black Beans and Peppers, Cooked	Skim Plain Milk
	Wednesday	Chicken	Crispy Chicken Sandwich	Watermelon, Fresh	x2 Plantain Slices and Cherry Tomatoes, Ranch	Skim Plain Milk
	Thursday	Vegetarian	Marinated Tofu with Brown Rice	Banana, Fresh	x2 Red Potatoes, Roasted	Skim Plain Milk
	Friday	Fish	Tuna with Pita Bread	Blueberries, Frozen	Baked Potato	Skim Plain Milk
MAX-HEI						
	Monday	Chicken	Curry Chicken with Flatbread	Apple, Fresh	Beans, Chickpea Salad and Cherry Tomatoes, Ranch	Skim Plain Milk
	Tuesday	Chicken	Crispy Chicken Sandwich	Banana, Fresh	x2 Broccoli, Roasted	Skim Plain Milk

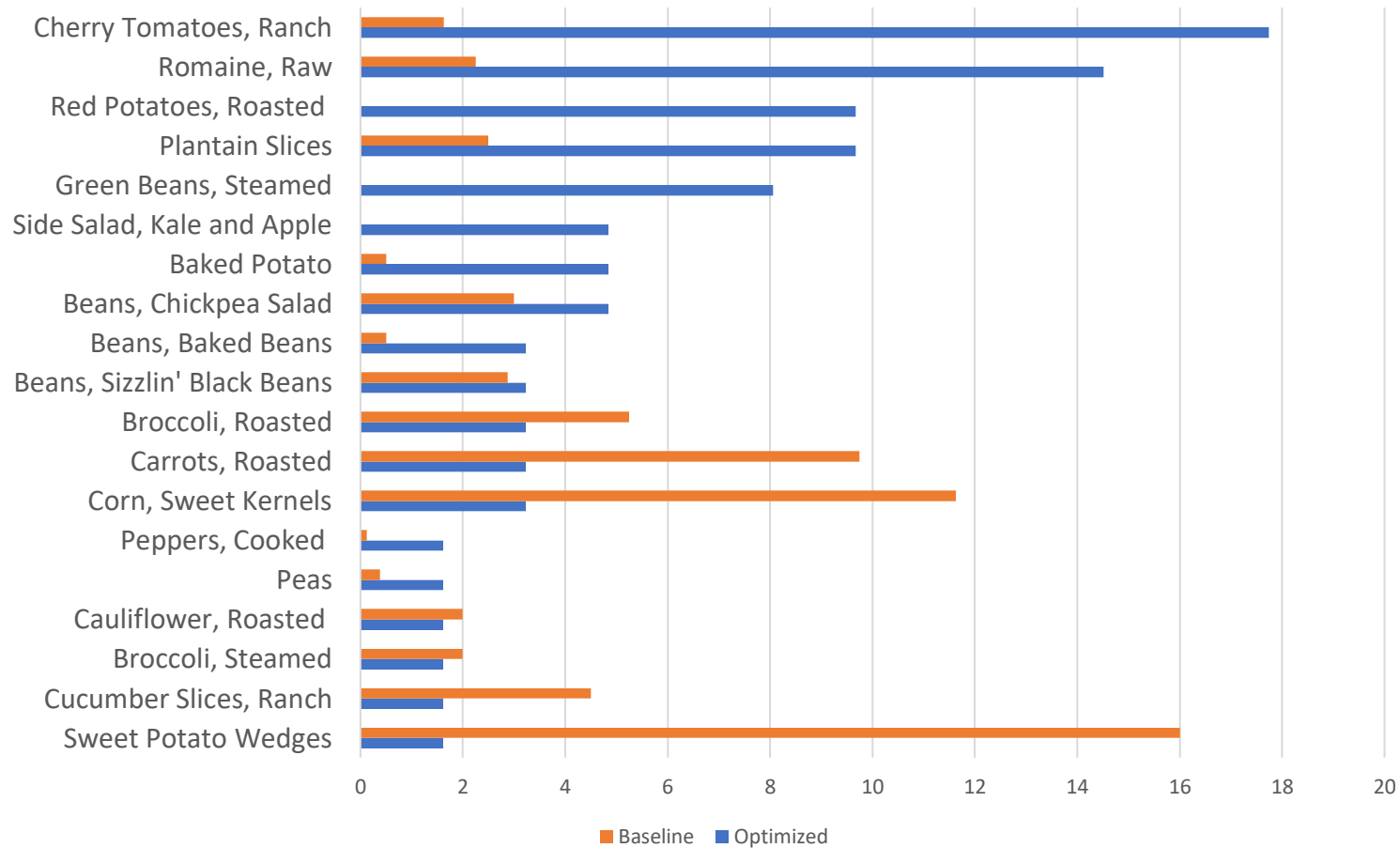
Wednesday	Vegetarian	Cheese Bites	Pear, Fresh	Romaine, Raw and Broccoli, Steamed	Skim Plain Milk
Thursday	Vegetarian	Marinated Tofu with Vegetable Fried Rice	Apple, Fresh	Romaine, Raw and Cherry Tomatoes, Ranch	Skim Plain Milk
Friday	Fish	Baked Fish in Chip with Brown Rice	Pear, Fresh	Corn, Sweet Kernels and Green Beans, Steamed	Skim Plain Milk

x2 = two servings of the vegetable

SI Figure 1. Fruit frequency for baseline and optimized weekly menus.



SI Figure 2. Vegetable frequency for baseline and optimized weekly menus.



SI Table 4. Baseline and optimized weekly menus nutrient content, as offered and consumed.

	Energy (kcal)		Fiber (g)		Calcium (mg)		Iron (mg)	
	Offered	Consumed	Offered	Consumed	Offered	Consumed	Offered	Consumed
Baseline	3039	1744	44	21	2798	1704	20	12
MAX-CALCON	3247	2436	38	28	2494	1752	26	19
MIN-COST	2829	1544	49	21	3105	1809	19	9
MAX-COSTCON	2918	2193	34	25	2184	1486	20	15
MAX-HEI	2754	1381	58	23	2062	1242	16	7
CON-COST-HEI-ENV	2774	1508	52	25	1913	1175	14	7
CON10-COST-HEI-ENV	3248	2094	58	32	1991	1257	15	9
CON30-COST-HEI-ENV	3248	2218	52	32	2287	1535	20	14

SI Table 4 Cont. Baseline and optimized weekly menus nutrient content, as offered and consumed.

	Polyunsaturated and Monounsaturated Fats (g)		Added Sugar (g)		Saturated Fat (g)		Sodium (g)		HEI	
	Offered	Consumed	Offered	Consumed	Offered	Consumed	Offered	Consumed	Offered	Consumed
Baseline	54	31	13	8	31	19	4.749	2.756	84.18	76.86
MAX-CALCON	58	44	15	11	23	19	5.002	3.737	91.84	86.39
MIN-COST	42	23	5	2	30	18	4.767	2.409	80.92	78.62
MAX-COSTCON	52	40	6	5	21	17	4.071	3.064	91.72	86.90
MAX-HEI	47	24	1	1	7	4	3.520	1.734	98.02	93.27
CON-COST-HEI- ENV	58	32	1	1	10	5	3.857	1.961	96.77	94.47
CON10-COST-HEI- ENV	71	45	1	1	10	7	3.575	2.091	99.80	92.45
CON30-COST-HEI- ENV	54	38	1	1	15	12	4.621	2.916	96.23	91.33

Appendix D: Additional Methods

Data

Environmental Life Cycle Assessment Data and Databases

Life cycle assessment databases and data on the environmental impacts of food production by commodity were available from a wide range of sources. Primarily data from the ecoinvent 3.6 database were used. The other resources described here were used in sensitivity analyses to assess the validity of ecoinvent data or as a supplement to the ecoinvent data where data was not available.

Ecoinvent

Ecoinvent is the world's leading Life Cycle Inventory (LCI) database. It contains well documented process data for thousands of products to help practitioners make informed decisions about environmental impact. The modeling guidelines for developing the ecoinvent database are consistent with ISO 14040 and 14044, and the International Reference Life Cycle Data System (ILCD) entry level requirements. Process data and models used for this research had a functional unit of 1 kg, system boundaries from cradle to farmgate unless otherwise specified, and used economic allocation and the cut-off approach which puts the burden of waste on producers incentivizing recycling. More information on the process data selected for this research is available in Appendix A and in the documentation for ecoinvent 3.6.

World Food LCA Database (WFLDB)

The World Food LCA Database (WFLDB) is like ecoinvent in that it is a detailed, transparent,

well-documented and reliable data source for accurate and comparable process data in the food sector. Many of the processes in ecoinvent for agriculture and food products were derived from the WFLDB. Given the similarities in the databases and overlap in LCIs, the WFLDB was used to validate results from ecoinvent. Life Cycle Impact Assessment was performed by staff at Quantis using multiple versions of the WFLDB in SimaPro and a range of impact assessment methods. These results were compared to the results from ecoinvent used in this study. Detailed documentation on the development and specifications of the WFLDB is available elsewhere.

database of Food Impacts on the Environment for Linking to Diets (dataFIELD)

The database of Food Impacts on the Environment for Linking to Diets (dataFIELD) is a database of the greenhouse gas (GHG) emissions, cumulative energy demand, and water scarcity of agricultural communities. Greenhouse gas emissions and cumulative energy demand estimates were assessed by performing a systematic review of human food environmental LCAs published between 2005 and 2016. Most studies were peer reviewed journal articles, and some reports, databases, and conference proceedings were used. The database primarily contains information from studies on European production. As with the WFLDB, data on the GHG of commodities in dataFIELD were used to validate results from ecoinvent on GHG emissions. Additionally, we used similar techniques for connecting commodity impacts to complex foods such as proxy groupings for missing data and conversion factors for removal of inedible parts. More information on dataFIELD can be found in the literature and the database is publicly available from the University of Michigan Center for Sustainable Food Systems.

Water scarcity data from dataFIELD were developed using spatially explicit irrigation data from U.S. agriculture, evapotranspiration models, and the AWARE impact assessment method which incorporates the difference between water availability and demand in a given region. As such, water scarcity is a more comprehensive measure of water impact than water consumption. This data became available in April 2021 after analyses and writing for the first aim were complete. Therefore, the first aim used water consumption data from ecoinvent and the second and third aim use data from dataFIELD on water scarcity.

Scientific Literature Environmental Impacts Estimates

Ecoinvent did not contain an LCI for egg production therefore process data on conventional production of Canadian chicken eggs compatible with openLCA and ecoinvent were provided by Nathan Pelletier. Detailed information on the development of this LCI is available from Pelletier et al. 2018 [1].

Additional datasets on the environmental impacts of agricultural commodities were used for sensitivity analyses and determining the validity of ecoinvent data [2-4]. These are available in the supplemental materials of published literature.

School Nutrition and Meal Cost Study

The SNMCS is the United States Department of Agriculture's (USDA) periodic assessment of the school meals program. The SNMCS addressed research questions in four broad domains: (1) school meal operations and food environments; (2) nutritional quality of meals; (3) meal costs and school revenue; (4) student participation, satisfaction, plate waste and dietary intakes. The

SNMCS explored the impact of the HHFKA by looking at changes in these four domains over time.

The SNMCS collected data from a nationally representative sample of public School Food Authorities (SFAs) and public non-charter schools participating in the NSLP. Data was collected during the 2014-2015 school year. Multiple methods of data collection were used. The data used for this study was collected from school nutrition managers using a web-based menu survey. The food and nutrition survey asked about the lunch served during one school week referred to as the “target week.”

Data from this study are publicly available upon request. This study used volume two data and worked closely with researchers at Mathematic Policy research Institute to ensure that all variables were properly interpreted and duplicate data was deleted.

Boston Public Schools

Data for this research was taken from the Boston Food Love Plate Waste Study (BFLPWS) which assessed two interventions in Boston Public Schools (BPS). The first intervention was a diffuse nutrition education program administered by FoodCorps members. The second intervention was the introduction of a salad bar to improve student vegetable selection during lunch.

The BFLPWS collected data from 13 schools and approximately 3,500 students. Repeated measures of students were taken in the fall (x2) and spring (x2) during the 2018-2019 school year. The interventions were assessed using student surveys and plate waste observations. The

first survey was administered in the cafeteria while students ate lunch. This survey asked about satiety after lunch and emotional state while in the cafeteria and was administered to students four times over the school year in conjunction with plate waste data collection. The second survey was administered in homerooms and asked about student food preferences, understanding of HHFKA policies, and attitudes toward school lunch staff and friends at lunch. This survey was only administered once to a small subset (n=150) of the study population.

Before plate waste data was collected, all items available for lunch that day were weighed repeatedly using the appropriate serving tools or serving sizes to assess starting weight variability. Plate waste data was collected from all students participating in lunch on the day of data collection. As students were served lunch a research assistant labeled the student's tray with their grade, homeroom, and name. Images of students' trays and point of sale data were recorded as students left the lunch line. After students finished eating, research assistants gathered lunch trays and weighed the remaining food items on the tray. Remaining food was weighed by item whenever possible. For example, meatballs were weighed separately of spaghetti, but tomato sauce was included in the weight of spaghetti.

Analysis

Life cycle assessment

Life cycle assessment is standardized by the International Organization for Standards. More information on the concepts necessary to perform an LCA can be found in the published standards online.

Data Integration

After environmental impact values were determined at the commodity level, they were connected to complex foods using federal government databases: What We Eat in America (WWEIA), Food and Nutrient Database for Dietary Studies (FNDDS), Food Commodities Intake Database (FCID), and Food Intakes Converted to Retail Commodities Database (FICRCD).

What We Eat in America is a national survey on dietary consumption conducted as part of the National Health and Nutrition Examination Survey. The survey collects two days of dietary intake data from a representative sample of Americans every two years. With this survey, a database of foods consumed in the U.S. is constructed in conjunction with the Food and Nutrient Database for Dietary Studies (FNDDS). The FNDDS is used for processing the food items and nutritional values of the WWEIA intakes.

The FNDDS includes information necessary for coding individual foods, portion sizes, recipes, and nutrient values of foods. The FNDDS is updated with each cycle of WWEIA. The FNDDS is also connected to the Food Patterns Equivalents Database for converting foods to food groups based on the Dietary Guidelines for Americans, the Food Commodities Intake Database (FCID), and the Food Intakes Converted to Retail Commodities Database (FICRCD). The later two are used for understanding the composition of foods by agricultural commodity. There are 8,690 food and beverage items in the most recent cycle of the FNDDS and WWEIA.

FNDDS codes are an eight-digit number which uniquely identifies a food or beverage. The first digit represents the major commodity groups: milk and milk products; meat, poultry, fish and

mixtures; Dry beans, peas, legumes, nuts, seeds; grain products; fruits; vegetables; fats, oils and salad dressings; sugars, sweets, beverages.

To assess dietary exposure to pesticides in the US, the Environmental Protection Agency (EPA) developed the FCID. The FCID translates food consumption reported in WWEIA to EPA-defined food commodities. The FCID includes 563 commodities derived from about 7000 WWEIA foods. The FCID recipes are used to convert food consumption reported in WWEIA to food commodities. This databased will be important for breaking down menu items into their component commodities for environmental impact assessment.

The FICRCD is very similar to the FCID in that it is used to convert dietary intakes into agricultural commodities. This database was developed by the USDA Agricultural Research Service (ARS) and Economic Research Service (ERS). This database contains 65 retail-level commodities for converting WWEIA foods.

References

1. Pelletier, N., *Changes in the life cycle environmental footprint of egg production in Canada from 1962 to 2012*. Journal of Cleaner Production, 2018. **176**: p. 1144-1153.
2. Poore, J. and T. Nemecek, *Reducing food's environmental impacts through producers and consumers*. Science, 2018. **360**(6392): p. 987.
3. Clune, S., E. Crossin, and K. Verghese, *Systematic review of greenhouse gas emissions for different fresh food categories*. Journal of Cleaner Production, 2017. **140**: p. 766-783.
4. Clark, M. and D. Tilman, *Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice*. Environmental Research Letters, 2017. **12**(6): p. 064016.