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Less animal protein and more whole grain in US school lunches could greatly reduce environmental impacts

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Altering dietary patterns is essential to ameliorating the environmental impacts of the world food system. The U.S. National School Lunch Program shapes the consumption of America's children and adolescents, providing a meaningful opportunity to reduce dietary environmental impacts. Here, we collate life cycle inventories relevant to the National School Lunch Program 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 ± SE impact per lunch was 1.5 ± 0.03 kg CO_2 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 phosphorus eq. freshwater and 3.1 ± 0.00 g nitrogen 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 National School Lunch Program, our results support increasing whole grain requirements and providing serving size or frequency limits for beef.

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High-income countries must shift their dietary patterns to address the increasing environmental burdens of food systems[1–3]. 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 guidelines[6]. 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 meals[7]. The program has an annual budget of 14 billion USD and in 2019, it provided lunch to nearly 40% of U.S. children daily[8]. 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 policy[11–17]. 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 documented[18–21]. 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. Lunch environmental impacts were driven by meat and

dairy and lunches with the greatest environmental impacts contained more meat, total protein, fruit, and starchy vegetables compared to lunches with the lowest impacts. Nearly 40% of lunch impacts were attributable to the 20% of lunches with the highest impacts, suggesting a need to alter these lunches to improve environmental outcomes.

Results

The School Nutrition and Meal Cost Study (SNMCS) collected data on over 2.2 million lunches served from a nationally representative sample of 1207 schools and included over 1300 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 elsewhere[9].

Linking the 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 school year 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 CO_2 eq. and the percentile cutoffs were as follows: 0.77, 0.99, 1.4, and 2.1 kg CO_2 eq. Lunches were assigned quintiles based on their impacts in relation to the cutoff values. A lunch with the GWP of 2.0 kg CO_2 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 (Fig. 1). The impacts of each lunch generally did not fall within the same quintile for all impact categories. For example, a

Table 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 m²a crop eq.	Water Consumption m³	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.
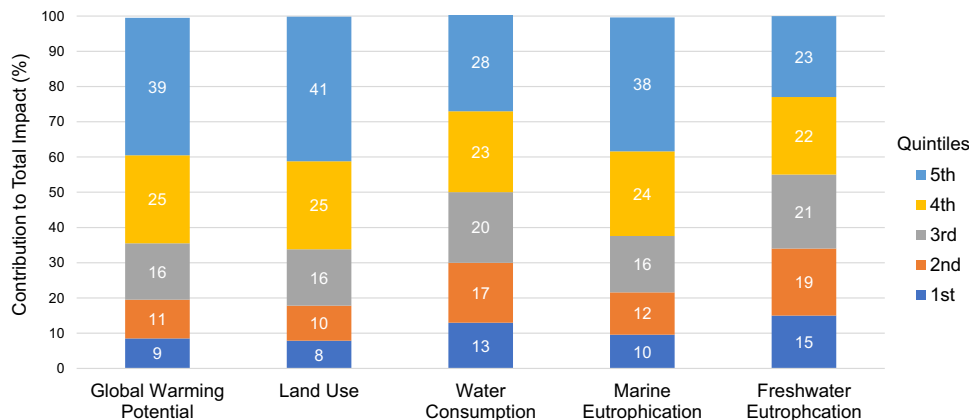
Fig. 1 Percent contribution of quintiles to the total environmental impact of lunches served in the National School Lunch Program by impact category. Caption: Lunch impacts for each impact category are divided into quintiles; each quintile represents 20% of lunches and is identified by a different color. 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.

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 (Supplementary Data 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 foods[22]. 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 starchy 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.

Table 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 vegetables	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[a]	0.00	1.02	0.00***
Poultry[a]	0.18	0.32	0.00**
Cured luncheon meat[b]	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[c]	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.
[a] Excludes cured luncheon meat.
[b] Cured luncheon meat contains poultry, beef, and pork.
[c] Milk is generally served in 8 oz. containers which is equivalent to 1 cup eq.
* <0.05.
** <0.01.
*** <0.001.

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

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**

Fig. 2 Total lunch composition and percent contribution of impacts from food groups for lunches served in the National School Lunch Program.
Caption: 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.

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 (Supplementary Data 2). Climate change, marine eutrophication, and land use rankings were the most consistent while water consumption was the least consistent.

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.

Table 3 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

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.

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 programs[27]. 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 school year 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 the 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 foods[26]. 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 destruction[38]. Fish produced in low-intensity, non-recirculating aquaculture could also be good options because they are associated with lower GWP than trawling fisheries[38]. 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 inexpensive[40].

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.

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 planning[43]. 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 outcomes[26]. 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 the 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.

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.

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 studies[21]. Most studies on the impacts of diets, including this work, end assessment at the farm or processor gate[20]. Although agriculture is the predominate driver of impacts, a full picture of impacts beyond the farm gate could be useful[26].

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 animals[26]. In 2018, 21% of beef consumed in the U.S. came from dairy systems[47]. 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.

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 improvement[48]. Finical incentives, like those provided for procuring local food, could encourage districts to offer beef less frequently[49]. 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 patterns[30–32]. Any changes however must be considered jointly with other dimensions of sustainable diets, USDA agricultural policy, and studies, which inform implementation.

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 elsewhere[50].

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 composition[51].

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 dishes[54].

FCID contains a series of recipes, which disaggregates foods commonly consumed in the U.S. into 563 unique agricultural commodities. The database contains over 7000 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 (Supplementary 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 imports[55]. 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 (Supplementary Data 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 elsewhere[52].

Analysis. Life cycle impact assessment results for agricultural commodities were calculated using ReCiPe 2016 Midpoint Hierarchical methods in openLCA 1.10.3[56]. 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 life cycle impact assessment results to account for removal of inedible parts, standard food preparation, and cooking losses (Supplementary Data 4). Conversion factors were derived from the Food Intakes Converted to Retail Commodities Database and other sources[57–59]. 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 (Supplementary Table 1). We then summed the weighted impacts across commodities for each food. This resulted in the impacts per 100 grams of each food, as served (Supplementary Table 2).

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 (Supplementary Table 3). 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.

Data availability
The data that support the findings of this study are available from ecoinvent but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of ecoinvent.

Code availability
The code to complete these analyses are available from the authors upon reasonable request.

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Author contributions

Conceptualization, A.S., N.T.B., C.E., and T.G; 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.

Competing interests

The authors declare no competing interests.

Additional information

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