Number of meal components, nutritional guidelines, vegetarian meals, avoiding ruminant meat: what is the best trade-off for improving school meal sustainability?

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Abstract

Purpose

School meals have the potential to promote more sustainable diets. Our aim was to identify the best trade-off between nutrition and the environment by applying four levers to school meals: i) reducing the number of meal components, ii) complying with the French school nutritional guidelines, iii) increasing the number of vegetarian meals, and/or iv) avoiding ruminant meat.

Methods

Levers were analyzed alone or in combination in seventeen scenarios. For each scenario, 100 series of 20 meals were generated from a database of 2316 school dishes using mathematical optimization. The nutritional quality of the series was assessed through the Mean Adequacy Ratio (MAR/2000 kcal). Seven environmental impacts were considered such as greenhouse gas emissions (GHGE). One scenario, close to series usually served in French schools (containing 4 vegetarian meals, at least 4 ruminant meat-based meals, and at least 4 fish-based meals) was considered as the reference scenario.

Results

Reducing the number of meal components induced an important decrease of the energy content but the environmental impact was little altered. Complying with school-specific nutritional guidelines ensured nutritional quality but slightly increased GHGE. Increasing the number of vegetarian meals decreased GHGE (from -11.7% to -61.2%) but decreased nutritional quality, especially when all meals were vegetarian (MAR= 88.1% against 95.3% in the reference scenario). Compared to the reference scenario, series with 12 vegetarian meals, 4 meals containing fish and 4 meals containing pork or poultry reduced GHGE by 50% while maintaining good nutritional quality (MAR=94.0%).

Conclusion

Updating French school nutritional guidelines by increasing the number of vegetarian meals up to 12 over 20 and serving non-ruminant meats and fish with the other meals would be the best trade-off for decreasing the environmental impacts of meals without altering their nutritional quality.

Keywords

Children; school meals; vegetarian; sustainability; nutritional guidelines; environmental impacts.

Abbreviations

ALA: Alpha-Linolenic Acid

GHGE: Greenhouse Gas Emissions

DHA: Docosahexaenoic Acid

ED: Energy Density

FR: Frequency Rule(s)

LA: Linoleic Acid

PP: Pork and Poultry

SFA: Saturated Fatty Acids

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Introduction

Human activities put major pressure on the environment. Anthropogenic greenhouse gas emissions (GHGE), as well as freshwater use, land use, and interference in nitrogen and phosphorus cycles induced by current food production contribute to a large extent to environmental changes [1–3]. The food sector accounts for around 26% of global GHGE [1]. Livestock production has higher environmental impacts compared to crop production. Shifting patterns of food choices towards less animal products can help in mitigating climate changes to stay within environmental limits [1, 2, 4].

Diet not only affects environment but also human health. Diets with plenty of fruit and vegetables and unrefined cereals contribute to the prevention of chronic diseases [5] while overconsumption of red and processed meat has been associated with higher risks of cardiovascular disease, type 2 diabetes, and colorectal cancer [5]. However, meat and fish contribute to the intakes of key nutrients such as zinc, iron, iodine, long-chain omega-3 fatty acids, and several vitamins, especially D and B12 [6, 7].

Sustainable diets are defined as "diets with low environmental impacts [. . .], culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe and healthy" [8]. Finding the best trade-off between nutrition and the environment might be challenging since both dimensions are not naturally compatible [9, 10]. Yet, if total removal of animal-based products from diets is likely to reduce their environmental impacts, their nutritional adequacy and acceptability might be impaired [11, 12].Transition to more plant-based diets should be done with attention to all the dimensions of sustainability [11].

School nutritional guidelines offer a wide range of opportunities for setting up more sustainable eating behaviors among children such as healthier eating choices [13], which are likely to be maintained in adulthood [14]. In the USA, western and northern countries of the European Union, and the United Kingdom, school meal programs were found to contribute to improving healthy eating habits [15, 16], tackling obesity [17], and enhancing academic performance [18]. In France, three quarters of nursery and primary school pupils eat at least one time per week in the school canteen [19]. They are registered for lunch on one or more days of the week. Each school week, 8.5 millions of school meals are served [20]. Unlike many other countries, French children cannot bring their own packed lunches unless they have health issues (e.g., food allergy). In addition to covering nutritional needs, the supply of school meals represents a lever for initiating the transition to more sustainable food systems. Improving school meal could contribute to preserve both children's health and the environment [21]. Since 2011, French school meals must fulfil compulsory nutritional guidelines regarding the number of components in a school meal and the type of dishes served [22, 23]. A simulation study found that complying with those guidelines provide better nutrition than when not respected [24], but the environmental impact was not assessed. In 2019, the service of at least one vegetarian meal per week (defined as a meal without meat or fish) became mandatory in France [25].

There is a known strong positive correlation between the quantity of food consumed and diet-related greenhouse gas emissions (GHGE) [26]. Therefore, reducing the number of components of meals could be a first step to reduce their environmental impacts. In addition, studies conducted in the USA, the UK, Spain, Italy, and Sweden, showed that the environmental impacts of school meals could be significantly decreased by limiting fish and meat, especially beef, in the menus [27–32].

The aim of the present study was to identify the best trade-off between nutrition and environment by applying four levers to school meals: i) reducing the number of meal components, ii) complying with the French school nutritional guidelines, iii) increasing the number of vegetarian meals, and/or iv) avoiding ruminant meat in non-vegetarian meals. Several scenarios were implemented to explore the four levers alone or in combination. Mathematical optimization was used to generate series of meals complying with the characteristics defined for each scenario, because it is a powerful method to simultaneously comply with a large set of different constraints [33–35].

Materials and Methods

French school meals are required to be composed of four or five components, i.e., a starter and/or a dessert, a protein dish, a side dish, a dairy product; most of them contain five components [23]. Portions sizes are not compulsory [36], except for industrial dishes (e.g. nuggets, chopped steak, sausages, pizzas …) [22]. French school dishes must also comply with rules regarding the frequency of service for fifteen types of dishes in a series of 20 consecutive meals (corresponding to 4 weeks of school) [22]. The fifteen types of dishes are defined by rules based on one or more characteristic(s). The combination of a type of dishes and an associated frequency forms a "frequency rule" (FR) (e.g., "starters containing more than 15% fat must be served no more than 4 times over 20 meals"). Note that one of the fifteen mandatory FR concerns the service of fish (fish or fish-based dishes containing at least 70% fish and having a ratio of proteins/fats ≥ 2 must be served at least 4 times over 20 meals) and another one concerns the service of ruminant meat (unground beef, veal, lamb, or offal must be served at least 4 times over 20 meals). In addition, since 2019, at least one vegetarian meal must be served per week (i.e., at least 4 times in a series of 20 meals) [25]. Then, in 2020, five additional (non-mandatory) rules, specifically regarding the composition of vegetarian meals, were released [37]. The 15 mandatory and 5 non-mandatory FR, called 15+5 FR, are detailed in Supplemental Table S1.

Based on a previously constituted database of dishes served at meals in primary schools in France (6- to 11-year-old children), a mathematical optimization approach was used to generate series of 20 meals according to seventeen different scenarios. Each scenario was defined by a given set of constraints related to i) the number of meal components (i.e., four or five components: a protein dish, a side dish, a dairy product, a starter and/or a dessert), ii) compliance with the 15+5 FR, iii) the number of vegetarian meals in a series of 20 meals, and iv) the avoidance of dishes containing ruminant meat in non-vegetarian meals.

School meal dishes database

An existing database from a previously published study by Vieux et al was used [24]. It is based on technical files (corresponding to the recipe for cooked dishes and to the mandatory labelled nutrient content and ingredients list for a ready to eat industrial dish) for dishes from 40 series of 20 school meals A main dish accounts for two components as it can either be a "protein dish" served with a "side dish" (e.g., a steak served with green beans) or a complete dish. A complete dish is a dish where the "protein dish" and the "side dish" are incorporated into the same main dish (e.g., lasagnas, gratins, chili con carne, etc.). In 2019, the initial database was expanded with a collection of technical files of vegetarian "protein dishes" and vegetarian "complete dishes" (n=206) [38]. The nutritional content of dishes was calculated by using CALNUT [39], Nutrinet-Santé [40], and CIQUAL 2013 [41] food composition tables. For the specific needs of this study, the environmental impacts of dishes were estimated by matching data taken from AGRIBALYSE database v3.0 [42], which provides fourteen different environmental indicators (obtained with the life cycle assessment method) for foods commonly consumed in France, to the expanded database.

The final database of school meal dishes contained 2136 dishes including 512 starters, 683 protein dishes (including 115 vegetarian protein dishes), 440 side dishes, 206 complete dishes (including 133 vegetarian complete dishes), 137 dairy products, 337 desserts and 1 bread. Each dish was characterized by the following information:

- fixed weight (in g), corresponding to its recommended or compulsory serving size for primary school children [36],
- component type (starter, protein dish, side dish, complete dish, dairy product, or dessert),
- ingredient content,
- energy and nutrient content,
- environmental impacts,
- vegetarian or not,

- industrial processing or not (needed for one of the non-mandatory 5 FR on vegetarian meals),
- compliance with FR-related type of dish (for instance “starters containing more than 15% fat”).

Generating series of 20 school meals according to seventeen different scenarios

Definition of the seventeen scenarios

To assess the nutritional and environmental impacts according to the four different levers (i.e., reduced number of meal components, compliance with French school nutritional guidelines, increased number of vegetarian meals, avoidance of ruminant meat), alone or combined, seventeen different scenarios were designed (**Table 1**). The French school nutritional guidelines (i.e., the 15+5 FR listed in table S1) apply to series of 20 consecutive meals, so that the scenarios generated series of 20 meals (made up of dishes from the school meal dishes database). Each meal contained a standard portion of bread (i.e., 40 g of French baguette).

Each of the seventeen scenarios was named according to the lever(s) tested:

- Reduced number of meal components: scenarios with four or five components were generated. The so-called ‘5C-‘ scenarios consisted of series of 20 five-components meals and ‘4C-‘ scenarios consisted of series of 20 four-components meals (i.e., 10 meals without dessert and 10 meals without starter).
- Compliance with French school nutritional guidelines: scenarios complying or not with the FR were generated. The ‘-FR’ scenarios consisted of series of 20 meals complying with the 15+5 FR.
- Increased number of vegetarian meals: scenarios with an increasing number of vegetarian meals were generated. The ‘*n*Veg’ scenarios consisted of series of 20 meals including a number (*n)* of vegetarian meals equals to 0 (no vegetarian meals), 4 (over 20 meals, corresponding to the current regulation of 1 weekly vegetarian meal), 8, 12, or 20. For example, series of 20 meals generated with the ‘5C-0Veg-FR’ scenario contained five-component meals without any (0) vegetarian meals.
- Avoidance of ruminant meat: scenarios excluding dishes containing ruminant meat were derived from the ‘*nVeg*” scenarios. Thus, in addition to fully vegetarian ones, two scenarios consisted of replacing 4 vegetarian dishes with fish-based meals (5C-16Veg-4Fish and 5C-16Veg-4Fish-FR*) and two scenarios consisted of replacing 8 vegetarian dishes with both fish and pork-based or poultry-based meals (5C-12Veg-4Fish-4PP and 5C-12Veg-4Fish-4PP-FR*) were generated.

When a ‘*n*Veg-FR’ scenario conflicted with one (or two) of the 15+5 FR, that FR was removed, and this was indicated by one (or two) star(s) at the end of the scenario name. Namely, the FR on ruminant meat was removed in the ‘5C-16Veg-FR*’ and ‘5C-12Veg-4Fish-4PP-FR*’ scenarios. It was also removed in the ‘5C-20Veg-FR**’ scenario, together with the FR on fish, to allow the service of 20 vegetarian meals.

Generation of one series of 20 meals

One series of 20 meals was generated by using the optimization method called binary integer linear programming [33]. The equations in the optimization model are detailed in Appendix 1. The model is characterized by *variables*, *constraints,* and an *objective function*:

- The *variables,* corresponding to the unknowns*,* were the 2136 dishes with fixed portions contained in the school meal dishes database.
- The *constraints*, corresponding to the requirement list, differed according to the scenario. *Common constraints* were shared by all the scenarios, e.g., exactly one dairy product and one bread per meal. Moreover, at each meal, there could be only one main dish, i.e., exactly one complete dish, or one combination of one protein dish and one side dish ,but not both. *Specific constraints* depended on the scenarios. In ‘5-C’ scenarios, every meal included both a starter and a dessert whereas in ‘4C-‘ scenarios, exactly 10 meals over 20 included a starter and 10 meals over 20 included a dessert. The series of 20 meals must comply with the 15+5 FR. The scenarios with ‘*n*Veg’, ‘4Fish’ or ‘4PP’ must comply with a frequency of *n* vegetarian meals, 4 fish-based meals and 4 pork-based or poultry-

based meals, respectively. Moreover, starters in vegetarian meals also could not contain meat or fish, starters in meals containing a fish dish could not contain meat, and starters in meals containing a pork or poultry (PP) dish could not contain fish, red meat, or processed meat.

- The *objective function*, corresponding to the goal of the optimization, simulated random picking among school meal dishes.

The resolution of each model resulted in an optimized series of 20 meals respecting all the constraints.

Generation of 100 different series of 20 meals

To generate the 100 series of 20 meals corresponding to one scenario, optimizations were performed in series within a loop. At each iteration, different dishes were picked so the 100 series were composed of different sets of dishes. The coding was programmed using SAS 9.4 software with MILP solver in OPTMODEL procedure.

Evaluation of nutritional quality and environmental impacts of the generated series of school meals

Nutritional quality of the series of meals

The nutritional quality of the series of meals was assessed through the average Mean Adequacy Ratio (MAR) for 2000 kcal, an indicator that estimates the average content of ‘positive’ nutrients expressed as a percentage of recommended intakes for children attending primary schools. Daily recommended values have been calculated taking into account the age and sex distribution of primary school children in France according to a previously described methodology [24]. The recommended values used in the computation of MAR are presented in Supplemental Table S2. The nutrients included in the MAR calculation were proteins, fibers, vitamins B1, B2, B6, B9, B12, C, D, E, and A, calcium, potassium, iron, magnesium, zinc, copper, iodine, selenium, linoleic acid (LA), alpha-linolenic acid (ALA), and docosahexaenoic acid (DHA). Then, the nutrient content of series was evaluated nutrient per nutrient. The level of each nutrient was considered ‘adequate’ if the average nutrient content of the meal was greater than or equal to 30% of the daily recommendation for that nutrient because lunch contributes to around 30% of daily caloric intake of French children [43]. Content in nutrients known to have adverse effects when consumed in high quantity, i.e., sodium, saturated fatty acids (SFA), total sugars, and free sugars [5], were also calculated to complete the evaluation of meals. Finally, energy density, an indicator of dietary quality found to be associated with selected predictors of obesity in children [44] was also calculated.

Environmental impacts of the series of meals

Environmental impact of the scenarios was assessed through their average greenhouse gas emissions (GHGE) as well as 6 additional indicators, namely acidification, water use, fossil resource use, freshwater eutrophication, marine eutrophication, and land use. GHGE is the best known climate change indicator [45]. Acidification results from chemical emissions in the atmosphere that are redeposited into ecosystems [45]. Water and fossil resource use correspond to the consumption of water (and its depletion in certain regions) and non-renewable energy resources (coal, gas, oil, uranium, etc.), respectively [45]. Freshwater and marine eutrophication correspond to excessive enrichment of natural environments with nutrients, which leads to proliferation and asphyxiation (dead zone) in freshwater and marine ecosystems [45]. Land use reflects the impact of an activity on land degradation, with reference to "the natural state" (i.e. without human intervention) [45].

Statistical Analysis

Nutrient content and environmental indicators were calculated for each series of 20 meals. For each scenario, the average nutritional quality and environmental impacts calculated across the 100 series of that scenario were compared with those from another scenario (**Table 1**, last column) and with those from a reference scenario using the t-test. According to the central limit theorem, the distributions of large samples (100 series) tend to be normal, regardless of the shape of the data so that normality could be assumed. The reference scenario was '5C-4Veg-FR' because it is close to the series of 20 meals usually served in France today, i.e., 20 meals of five components complying with FR including a weekly vegetarian meal. The content of "positive" nutrients included in the MAR, expressed as percentage of the daily recommendation, were also compared to the theoretical 30% threshold using the t-test for one sample.

Statistical analyses were performed with R software version 4.0. The level of significance was set to 5% for all the tests. To facilitate the interpretation of results, nutrient content and environmental values were presented per meal. Here, "meal" is defined as the average value for a complete series of 20 meals divided by 20.

Results

Nutritional quality and GHGE of series of meals, according to the number of meal components

Reducing the number of components from 5 to 4 reduced the average energy content of meals (**Fig. 1a**) and their GHGE (**Fig. 1c**) but also reduced, moderately but significantly, their MAR (**Fig. 1b**), whether FR were imposed or not. When FR were fulfilled, reducing the number of meal components decreased the average energy content per meal from 712 kcal (in the reference 5C-4Veg-FR scenario) to 609 kcal (in the 4C-4Veg-FR scenario). For information, 30% of the recommended daily energy intake for French children of primary school age represents 599 kcal (Supplemental Table S2), a level close to the median energy content of meals in the 4C-4Veg-FR scenario (Fig. 1a). This means that almost half of the series with 4-components meals and fulfilling the FR provide less than the recommended level of energy intake.

Nutritional quality and GHGE of series of meals, according to compliance with frequency rules, number of vegetarian meals, and avoidance of ruminant meat

Compared to scenarios without FR, series of meals generated with –FR scenarios had significantly lower energy content, except when not all 15+5 FR were fulfilled (i.e. –FR* and –FR** scenarios) (**Fig. 2a**). Moreover, energy increased slightly with the number of vegetarian meals (it was maximum for 5C-20Veg-FR**).

Average MAR (**Fig. 2b**) decreased when the number of vegetarian meals increased, with the lowest values obtained when all twenty meals were vegetarian (i.e., 5C-20Veg and 5C-20Veg-FR** scenarios). Applying all FR improved the MAR. Applying FR also improved the MAR in the last scenario (5C-12Veg-4Fish-4PP-FR*) where all FR were applied except that ruminant meat was replaced by poultry or pork.

SFA and fat content decreased when the numbers of vegetarian meals increased (Supplemental Tables S3 and Fig. S4): % energy from fats ranged between 28.3% to 36.1% and % energy from SFA kept below 12% (i.e., the French recommended level for SFA) in series with at least 12 vegetarian meals (fulfilling FR). Free sugars and SFA significantly decreased when FR were applied. Whatever the scenario, % energy from free sugars was between 4.90% and 6.22%, well below the recommended level of 10%.

Average GHGE per meal decreased when the number of vegetarian meals increased (**Fig. 2c**). The effect of imposing FR on GHGE varied depending on the number of vegetarian meals and the presence of ruminant meat. Imposing FR tended to increase GHGE in series containing from 0 to 12 vegetarian meals, but it tended to decrease GHGE when ruminant meat was avoided (i.e., in –FR* and –FR** scenarios).

Whether or not the FR were imposed, the average GHGE per meal were by far the lowest in the series generated when ruminant meat was avoided.

Whatever the scenario, average nutrient content was well above 30% of the daily recommendation for most nutrients (**Fig. 3a, 3b, 3c**), except for ALA, DHA (**Fig. 3a**)., vitamin B3 and vitamin D (**Fig. 3c**).

Applying FR to the scenarios significantly increased the average fiber, vitamin B9 and vitamin C content as well as DHA, potassium, zinc, and selenium content in most of the scenarios, and significantly decreased the average content of linoleic acid, alpha-linolenic acid (only for scenarios with at least 8 vegetarian meals) and vitamin E (only for scenarios with at least 12 vegetarian meals). When the FR were applied and the proportion of vegetarian meals in the scenarios increased, fiber, calcium, iron (only for scenarios with at least 8 vegetarian meals), magnesium and vitamin B9 contents significantly increased, but DHA, zinc, vitamins B1, B2, B3, B6, B12, and D content significantly decreased. In the fully vegetarian scenario, the average DHA and vitamin B3 content was below 30% of daily recommendation, while the content in other scenarios following the FR were not. Vitamin D content was also higher in non-vegetarian scenarios than in the fully vegetarian scenario but still did not reach the 30% of daily recommendation.

Environmental impacts of series of meals, according to compliance with frequency rules, number of vegetarian meals, and avoidance of ruminant meat

As compared to the meals generated with the 5C-4Veg-FR reference scenario, environmental impacts significantly increased when there were no vegetarian meals (5C-0Veg-FR) and significantly decreased when the number of vegetarian meals increased (except for water use in the 5C-8Veg-FR scenario) (**Table 3**). In the scenarios avoiding ruminant meat (5C-20Veg, 5C-20Veg-FR**, 5C-16Veg-4Fish, 5C-16Veg-4Fish-FR* 5C-12Veg-4Fish-4PP and 5C-12Veg-4Fish-4PP-FR*), compared to the reference scenario, GHGE were reduced by 47.6% to 61.2 %. When considering only scenarios complying with all the 15+5 FR, GHGE could not be reduced by more than 24.7 % (5C-12Veg-FR).

Compared with no FR applied, imposing FR significantly increased the environmental impacts of meals, except for fossil resource use and freshwater eutrophication and except for the fully vegetarian scenarios (Table 3 and see Supplemental S5 Fig. S6 for all paired comparisons).

Discussion

The series of 20 school meals generated with the reference scenario (i.e., 5C-4Veg-FR), which is the closest to what is commonly served in French schools, displayed high nutritional quality (95.3% adequacy for 2000 kcal) and GHGE of 2.0 kg CO2 eq. on average per meal. Compared to this reference, none of the tested scenarios proved able to simultaneously reduce GHGE (and other environmental impacts) while increasing (or at least maintaining) such high nutritional quality. The best GHGE reduction that can be achieved when all the current FR were applied was a reduction of 25 % and was obtained with 12 vegetarian meals. However, by changing only the FR on ruminant meat, it was possible to further decrease GHGE (by -50%) without impairing nutritional quality.

The first lever tested in this study to improve the sustainability of school meals was to reduce the number of components by removing either the starter or the dessert from the meals. However, this path was underwhelming, because it led to a relatively small environmental impacts reduction (around 8% of reduction for GHGE). Yet, serving four components instead of five induced an important reduction of the energy content of the meals, leading to a median energy content of 600 kcal per meal when fulfilling all the FR instead of 707 kcal in 5C-4Veg-Fr (Fig. 1a). Interestingly, this reduced level corresponds both to the estimated energy requirement of primary school children at lunch (i.e. 599 kcal taking into account the age and sex distribution of primary school children in France [24] and considering that 30% of daily energy intake is consumed at lunch) and to the average energy intake consumed at lunch in school by children as recently reported by the French Agency for Food Environmental and Occupational Health & Safety (i.e. 590 kcal on average for children in nursery and primary schools [19]). A positive consequence of offering just what is needed on average could be to reduce food waste. However, a negative consequence could be that the quantities offered may not be sufficient for all the children with energy needs higher than the average, unless the portions served are adapted to the individual needs of each child which is not so easy to implement. Moreover, fulfilling all the frequency rules with only four-component meals does impose the service of only raw vegetables as starters and of mostly raw fruits as desserts (8 times out of the 10 meals with dessert). It reduces school meals diversity because the service of traditional starters (e.g., quiches, mimosa eggs) as well as new type of starters (e.g. egg rolls) is no longer possible and the introduction of sweet desserts and pastries is largely restricted. Such changes are likely to be little appreciated by children today and would thus reduce the acceptability of the series of meals.

The second lever tested was the compliance with nutritional standards and the results showed its positive impact on nutritional quality, which confirms a previous study on nutritional quality of French school meals [24]. However, in the present study, following French school nutritional guidelines was also found to have a deleterious impact on the environmental dimension because of the high environmental cost of imposing at least four ruminant meat-based meals and four fish-based meals over twenty meals. A study conducted in the UK also found that following national food-based standards for school meals would increase GHGE generated by the meals [47]. In fact, in both France and the UK, school-specific nutritional guidelines were created to ensure adequate nutritional quality of meals served at school, without considering their environmental impact. Nutritional guidelines for school meals now need, similar to national food based dietary guidelines [48], to consider sustainability dimensions other than nutrition in their update. In France, the obligation, since 2019, to serve one vegetarian meal per week at school, goes in that direction [25].

The third lever tested was the increase in the number of vegetarian meals in the series of 20 meals, which was found to decrease their environmental impacts but also to decrease their overall nutritional adequacy. Beyond the decrease of overall nutritional quality associated with the increasing number of vegetarian meals, some nutrient content increased (fiber, calcium, iron, magnesium, and vitamin B9) while others decreased (DHA, zinc and vitamins B1, B2, B3, B6, B12, and D), which is consistent with a previous study comparing vegetarian with non-vegetarian main dishes [38]. Regarding the reduction of the environmental impacts, it is in line with previous studies showing that school meals including fish and meat have higher GHGE [28, 49] or higher aggregate Recipe score [50] than vegetarian meals.. A trade-off must therefore be found by introducing more vegetarian meals to decrease the environmental impacts but without reaching extreme situations (such as the fully vegetarian scenarios) which may compromise the coverage of the nutritional requirements of children.

The fourth lever tested was the avoidance of ruminant meat. Following the French nutritional guidelines for school meals (i.e., the FR), a series of 20 consecutive meals must contain at least four ruminant meat-based meals. Our results showed that replacing that frequency rule with a constraint imposing the service of four meals containing pork or poultry would dramatically (and significantly) decrease GHGE, acidification and land use (by approx. one third) and would moderately (but still significantly) decrease marine eutrophication, with no effect on freshwater eutrophication, fossil resource use and water use (Supplemental Fig. S6), without impairing the overall nutritional quality of meals. In older Dutch adults, drastic reduction of GHGE could also be achieved by replacing ruminant meat and processed meat by pork and poultry while staying in line with Dutch food-based dietary guidelines [51]. In studies assessing the carbon footprints of school meals in the UK and Europe, ruminant meat-based meals, and more broadly red meat-based meals, were the main contributors of GHGE [29, 30, 47, 52] and water consumption [29, 30]. Reducing ruminant meat seems able to reduce the environmental impacts without degrading the nutritional quality of meals [31, 32, 52] (provided that relevant substitutions are made, e.g., with white meats [52]). Choosing white meat as more sustainable alternative to red meat or processed meat may lead to health benefits as high consumption of white meat is associated with lower risks of all-cause mortality [53]. However, the total removal of ruminant meat may compromise the acceptability of meals because children tend to prefer familiar dishes [54]. In order to better satisfy this sustainable diets dimension, intermediate solutions might be proposed by still serving red meat but in reduced amounts as shown with "low-carbon" school meals proposed by the Municipality of Barcelona [31]. "Low-carbon" meals offered in several schools in Barcelona still contain chicken, fish, and even red meat, but in smaller amounts compared to the meals commonly served in other schools of the municipality. "Low-carbon" meals lead to an increase of overall nutritional quality from 6 to 47%, according to the "Rich Meal Index", and reductions of environmental impacts.

Based on our work, we can draw perspectives for future recommendations on sustainable school meals. Nutrient per nutrient analysis showed that school meals were not able to provide adequate vitamin D and ALA intakes. Omega 3 fatty acids are essential nutrients to improve cognitive performance [55]. Choosing fats rich in omega 3 for seasoning could increase the omega 3 fatty acid content of meals. In order to successfully move towards more vegetarian meals at school, it is necessary to have the support of the children but also the involvement of the parents and all the professionals (e.g., kitchen staff, dieticians, municipality staff) involved at different stages of school catering [54]. Since they are not well known, vegetarian dishes may be rejected by professionals, parents, and children [56]. A policy that trains catering cooks to provide attractive plant-based dishes to children [57] associated with adapted communication to parents may lead to the successful implementation of more vegetarian meals in French schools. Nutrients levels lower or close to 30% of daily recommendation in the school meals generated in our study (LA, ALA, DHA, calcium, potassium, zinc, vitamins B1, B2, B3, B6, C, and D) may be critical for children from disadvantaged populations. Indeed, breakfast or dinner skipping is more frequent in children from lower than from higher socio-economic status [43]. In France, many municipalities apply for a long-term social pricing of the meals (the price paid is calculated based on parent's income) [58]. Moreover, since January 2021, each meal offered at less than 1€ can be funded by the government up to 3€.

The first limitation of this work is that our analysis focused on the food offered not the meals consumed. Food leftovers could not be considered even though they have a significant impact on cost [59, 60], environment [59], and nutrient intake [60, 61], because of missing robust data on the proportion and kind of food component usually wasted at consumption. Data available indicates that cooked vegetables remain the least favorite food category among French school dishes [62]. However, school needs to play its educational role by exposing adequate amounts of healthy foods to children with the potential effect to change their liking [63]. The second limitation is that the compliance with some scenarios, namely scenarios with only four-component meals or scenarios completely avoiding ruminant meat, would induce dramatic changes in school meal composition. Adapting portion size [64] could be a promising strategy to reduce the environmental impacts while maintaining cultural acceptability. The possibility to mix 4-components and 5-compoments meals could also be tested, as well as imposing a diversity of species among the meat dishes served (instead of totally removing ruminant meat). Recipe reformulation through optimization may be another solution to be addressed, but was beyond the scope of the present study. A third limit is that the bioavailability of nutrients such as iron or zinc, which may be lower in vegetarian than in non-vegetarian meals, was not assessed. Bioavailability is nonetheless moderately impacted when the diet is diversified, even when the animal to plant ratio is relatively low [65]. A fourth limit is that scenarios don't consider production constraints (e.g., total time needed to prepare a meal) or acceptability constraints (e.g., children's preferences, likely or unlikely association between dishes, etc.). But the aim of this work was more to identify levers for improvement rather than providing a turnkey meal plan. The last limitation is that we did not consider meal cost, but other studies found that reduction of GHGE is compatible with affordable school meals [32, 35].

The major strength of this study is the application of the optimization approach on a unique database of around 3000 school dishes available in France, for which nutritional and environmental data were collected. Optimization is a flexible approach for planning sustainable school meals because constraints on nutrient content [33–35, 66, 67], cost [34], and acceptability [33, 68] can be easily added, as also shown in the Swedish context [32]. Our results could potentially be extended to other school levels or other mass catering systems (student or worksite cafeterias, nursing homes, etc.). However, further analysis would be necessary to estimate the real impact of these changes on the food system. In particular, the scenario with no ruminant meat is likely to destabilize the agricultural sector in France.

Conclusion

According to the present study, the best trade-off for decreasing the environmental impacts of French school meals without altering their nutritional quality is to increase the number of vegetarian meals up to 12 over 20 and to serve non-ruminant meats and fish with the other meals. Updating school-specific nutritional guidelines in that direction would impact not only children but also all actors throughout the supply chains in public procurement, representing an unbeatable start for moving toward more sustainable food systems.

Appendix 1

Binary integer linear model used to generate one series of twenty meals according to one of the 17 scenarios

<u>Variables and objective function:</u>

The unknown were binary variables $x(d,m)$ where d is the dish ($d = 1,..,2136$) and m is the meal ($m = 1,..,20$) in the series. If $x(d,m) = 1$,it means dish d was selected in meal m by the algorithm but if $x(d,m) = 0$, it means dish d was not selected in meal m.

The optimization process was used to simulate random picking among school meal dishes. To do so, a coefficient $r(d,m)$ corresponding to a random continuous number between 1 and 1000 was assigned to each variable $x(d,m)$. The single-objective function consisted of minimizing the sum of each variable multiplied by its random coefficient as indicated in Equation (1). To allow uniform distribution among complete dishes and protein and sides dishes, $r(d,m)$ was divided by 2 for protein and side dishes.

$$f(x) = min \sum_{d=1}^{2136} \sum_{m=1}^{20} x(d,m) \times s(d,m), \quad s(d,m) = \frac{r\,(d,m)}{n}, \qquad r\,(d,m) \in [1;1000] \;\; (1)$$

$$n = 2 \; if \; d \in \{protein\ dishes, side\ dishes\}, n = 1 \; if \; d \notin \{protein\ dishes, side\ dishes\}$$

<u>Common constraints</u>

Some constraints on the format of meals were shared by all the scenarios. There could be exactly one dairy product and one bread per meal as shown in Equation (2) and (3).

$$\sum_{\substack{d \in dairy \\ products}} x(d,m) \; = 1, \qquad m = 1, \ldots, 20 \;\; (2)$$

$$\sum_{d = bread} x(d,m) \; = 1, \qquad m = 1, \ldots, 20 \;\; (3)$$

At each meal, there could be only one main dish. Equation (4) showed there could be exactly one complete dish, or one combination of one protein dish and one side dish per meal, but not both.

$$\sum_{\substack{d \in complete \\ dishes}} x(d,m) \; + \; 0.5 \times \sum_{\substack{d \in protein \\ dishes}} x(d,m) + 0.5 \times \sum_{\substack{d \in side \\ dishes}} x(d,m) = 1, \qquad m = 1, \ldots, 20 \; (4)$$

$$with \sum_{\substack{d \in protein \\ dishes}} x(d,m) \; \leq 1, \qquad \sum_{\substack{d \in side \\ dishes}} x(d,m) \; \leq 1 \; and \sum_{\substack{d \in complete \\ dishes}} x(d,m) \; \leq 1$$

<u>Specific constraints</u>

For '4C-' and '5C-' scenarios:

In '5-C' scenarios, every meal included both starter and a dessert as shown in Equation (5) whereas in '4C-' scenarios, exactly 10 meals over 20 included a starter and 10 meals over 20 included a dessert as shown in Equation (6).

$$\sum_{d \in starters} x(d,m) \; = 1 \; and \sum_{d \in desserts} x(d,m) \; = 1, \qquad m = 1, \ldots, 20 \; (5)$$

$$\sum_{m=1}^{20} \sum_{d \in starters} x(d,m) \; = 10 \; and \sum_{m=1}^{20} \sum_{d \in desserts} x(d,m) \; = 10 \; (6)$$

For '-FR', 'FR' and '-FR*' scenarios:*

The series of 20 meals must comply with the 15 mandatory FR and 5 recommended FR for vegetarian meals. For example, Equation (7) shows the constraint for maximum FR and Equation (8) for the minimum FR with $c_i(d)$ the compliance of dish d with the i-est FR where $c_i(d) = 1$ if complied with, and $c_i(d) = 0$ otherwise.

$$\sum_{m=1}^{20} \sum_{d=1}^{2136} x(d,m) \times c_i(d) \leq MAX \ (7)$$

$$\sum_{m=1}^{20} \sum_{d=1}^{2136} x(d,m) \times c_i(d) \geq MIN \ (8)$$

For ‘nVeg’, ‘4Fish’ and ‘4PP’ scenarios:

The scenarios with ‘*n*Veg’, ‘4Fish’ or ‘4PP’ must respect a frequency of *n* vegetarian meals, 4 fish meals and 4 PP meals, respectively, as specified in Equations (9), (10), and (11).

$$\sum_{m=1}^{20} \sum_{\substack{d \,\in\, vegetarian \\ dish}} x(d,m) \ = n \,, \qquad n \in \{0; 4; 8; 12; 16; 20\} \ (9)$$

$$\sum_{m=1}^{20} \sum_{\substack{d \,\in\, fish \\ dish}} x(d,m) \ = 4 \ (10)$$

$$\sum_{m=1}^{20} \sum_{d \,\in\, PP\, dish} x(d,m) \ = 4 \ (11)$$

Moreover, starters in vegetarian meals also could not contain meat or fish (Equation (12)), starters in meals containing a fish dish could not contain meat (Equation (13)) and starters in meals containing a PP dish could not contain fish, red meat, or processed meat (Equation (14)).

$$\sum_{\substack{d \,\in\, vegetarian \\ dish}} x(d,m) + \sum_{\substack{d \,\in\, starter\ with \\ fish\ or\ meat}} x(d,m) \leq 1, \qquad m = 1, \dots, 20 \ (12)$$

$$\sum_{\substack{d \,\in fish \\ dish}} x(d,m) + \sum_{\substack{d \,\in\, starter\ with \\ meat}} x(d,m) \leq 1, \qquad m = 1, \dots, 20 \ (13)$$

$$\sum_{\substack{d \,\in\, PP \\ dish}} x(d,m) + \sum_{\substack{d \,\in\, starter\ with \\ fish,\ \ red\ or\ processed\ meat}} x(d,m) \leq 1, \qquad m = 1, \dots, 20 \ (14)$$

Declarations

Conflicts of interest/Competing interests: The authors have no conflicts of interest to declare

Authors' contributions : All authors contributed to the study concept and design. Data collection and analysis were performed by Romane Poinsot. The first draft of the manuscript was written by Romane Poinsot and all authors commented and modified previous versions of the manuscript. All authors read and approved the final manuscript.

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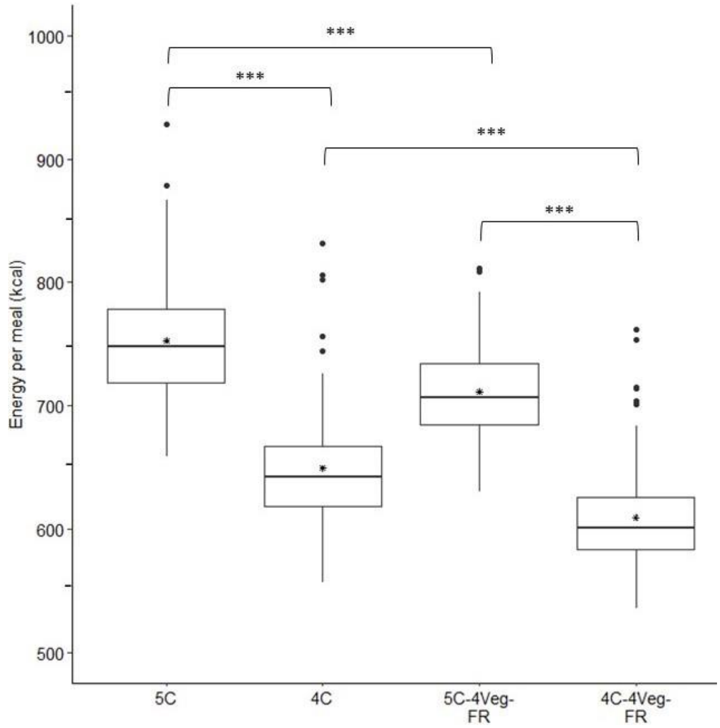
Table 1 Number of vegetarian, fish-based, ruminant meat-based, and pork or poultry-based meals[1] and paired scenarios for comparison for each of the seventeen scenarios of 100 series of 20 meals.

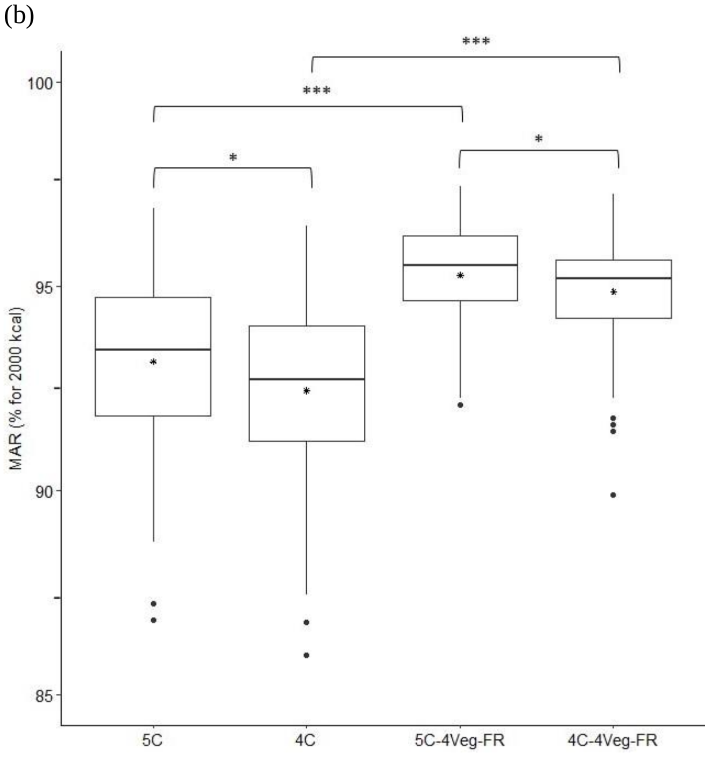
Scenario (100 series of 20 meals)	Components (n)	Vegetarian meals (n)	Fish-based meals (n)	Ruminant meat-based meals (n)	Pork-based and poultry-based meals (n)	Paired scenario to be compared with (except 5C-4Veg-FR)
5C	5	0 to 20	0 to 20	0 to 20	0 to 20	4C
4C	4	0 to 20	0 to 20	0 to 20	0 to 20	5C
5C-0Veg	5	0	0 to 20	0 to 20	0 to 20	5C-0Veg-FR
5C-0Veg-FR	5	0	4 to 16	4 to 16	0 to 12	5C-0Veg
5C-4Veg	5	4	0 to 16	0 to 16	0 to 16	
5C-4Veg-FR	5	4	4 to 12	4 to 12	0 to 8	All
4C-4Veg-FR	4	4	4 to 12	4 to 12	0 to 8	4C
5C-8Veg	5	8	0 to 12	0 to 12	0 to 12	5C-8Veg-FR
5C-8Veg-FR	5	8	4 to 8	4 to 8	0 to 4	5C-8Veg, 5C-12Veg-FR
5C-12Veg	5	12	0 to 8	0 to 8	0 to 8	5C-12Veg-FR
5C-12Veg-FR	5	12	4	4	0	5C-12Veg, 5C-8Veg-FR, 5C-20Veg-FR**
5C-20Veg	5	20	0	0	0	5C-20Veg-FR**
5C-20Veg-FR**	5	20	0	0	0	5C-20Veg, 5C-12Veg-FR
5C-16Veg-4Fish	5	16	4	0	0	5C-16Veg-4Fish-FR*
5C-16Veg-4Fish-FR*	5	16	4	0	0	5C-16Veg-4Fish, 5C-20Veg-FR**, 5C-12Veg-4Fish-4PP-FR*
5C-12Veg-4Fish-4PP	5	12	4	0	4	5C-12Veg-4Fish-4PP-FR*
5C-12Veg-4Fish-4PP-FR*	5	12	4	0	4	5C-12Veg-4Fish-4PP, 5C-12Veg-FR, 5C-16Veg-4Fish-FR*

5C-4Veg-FR: reference scenario. '5C-': series of 20 meals with five components (1 starter, 1 protein dish, 1 side dish, 1 dairy product, 1 dessert, plus 40 g of bread); '4C-': series of 20 meals with four components:10 meals without dessert and 10 meals without starter; '*n*Veg': *n* vegetarian meals; '4Fish': 4 fish-based meals; '4PP': 4 pork-based or poultry-based meals; '-FR': series of 20 meals complying with the 15 mandatory and 5 non-mandatory frequency rules (FR) (Supplemental Table S1) '-FR**': all the FR excluding that for fish and that for ruminant meats '-FR*': all the FR excluding that for ruminant meat.

(a)


Energy per meal (kcal)
1000
900
800
700
600
500
***
***
***
***
5C
4C
5C-4Veg-FR
4C-4Veg-FR

(b)


MAR (% for 2000 kcal)
100
95
90
85
***
***
*
*
5C
4C
5C-4Veg-FR
4C-4Veg-FR

(c)

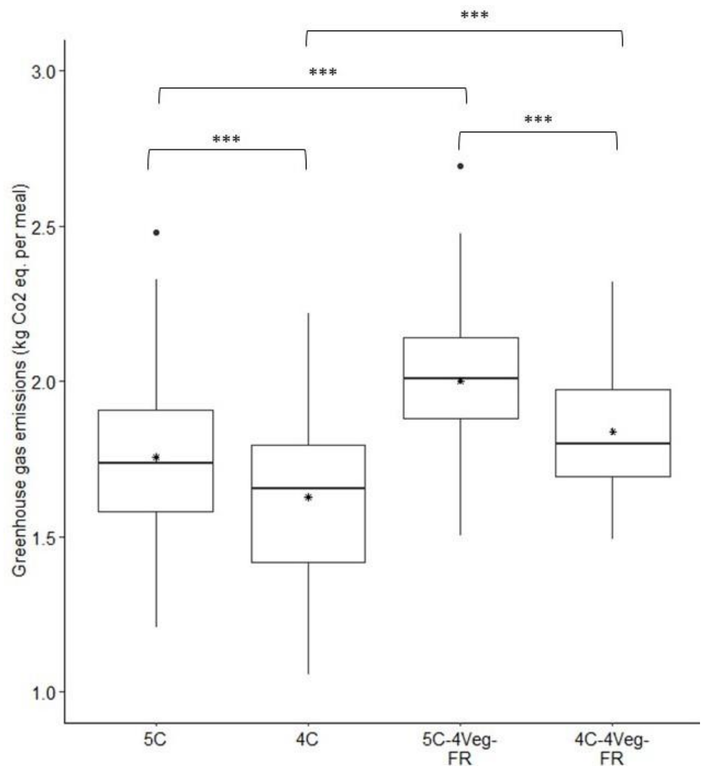
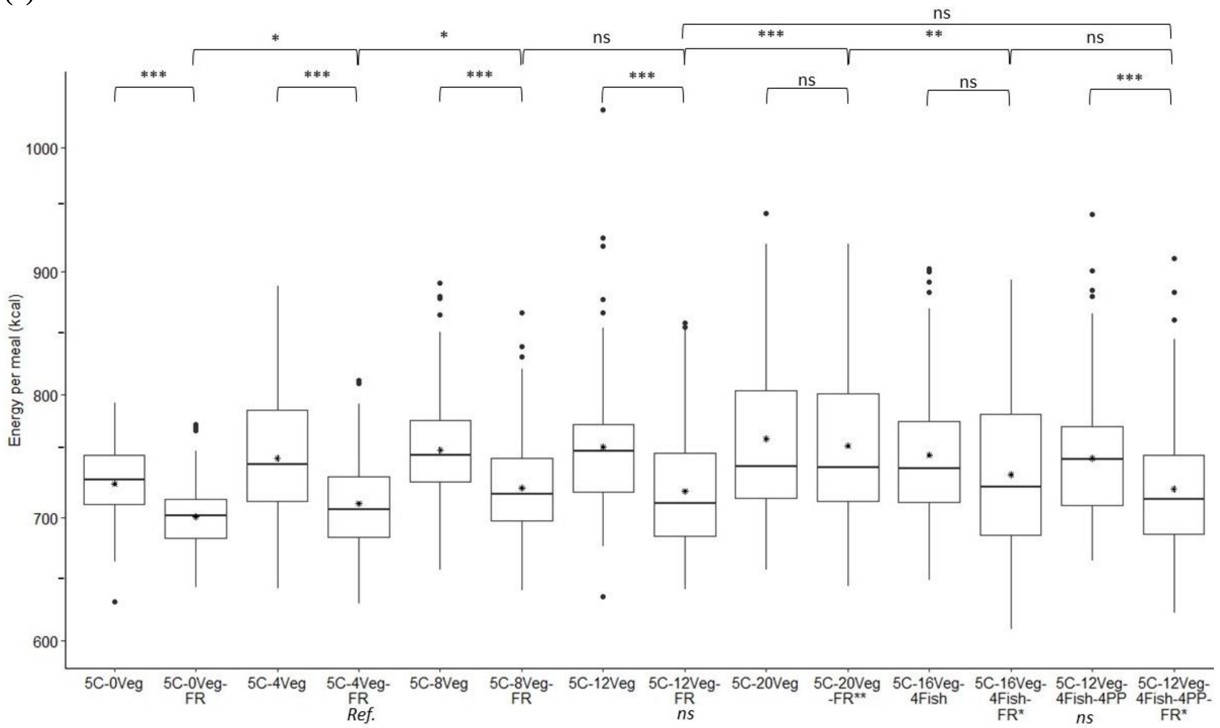
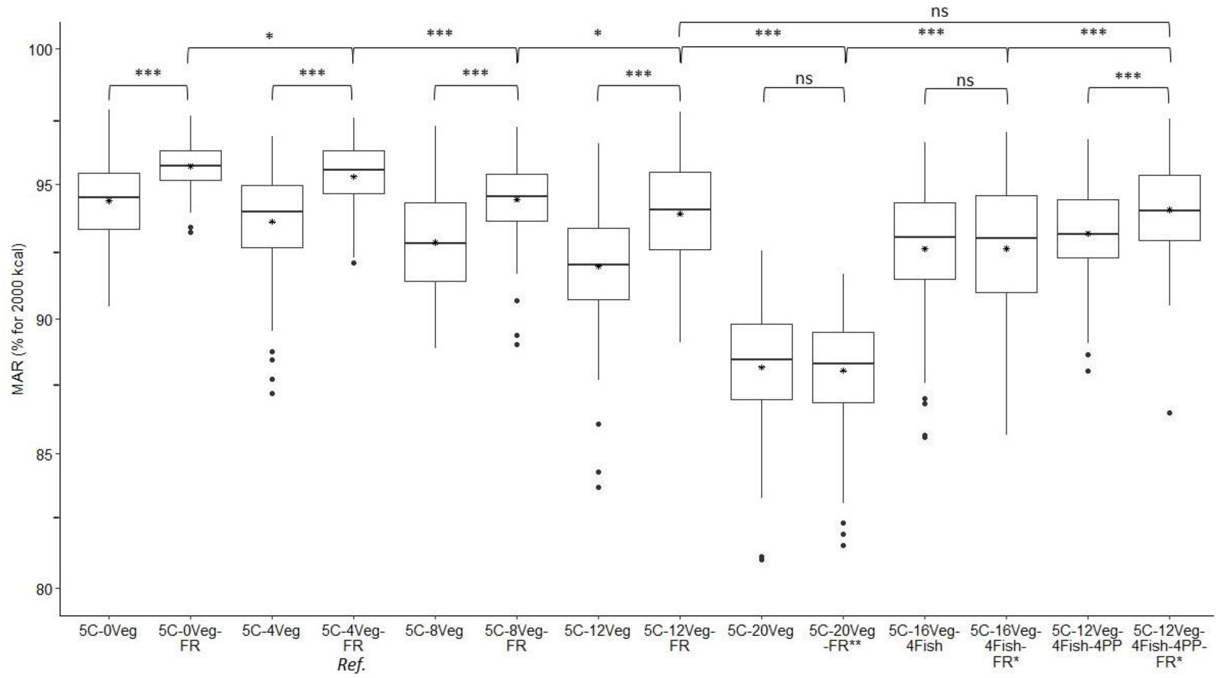


Fig.1 a) Energy per meal (kcal); **b)** Mean Adequacy Ratio (MAR) (% for 2000 kcal) and **c)** Greenhouse Gas Emissions (GHGE) (kg CO_2 eq.) of meals, in the series of 20 meals (n=100) generated with '5C', 4C', '5C-4Veg-FR' and '4C-4Veg-FR' scenarios. Energy, MAR, and GHGE were compared between two scenarios using t-test. '***' p-value <0.001 '**' p-value <0.01 '*' p-value <0.05 'ns': not significant. The boxplots show the distribution of data based on five sets (minimum, first quartile, median, third quartile, maximum) and the star represents the mean. For example, for energy per meal (a) in '5C' scenario, minimum=659 kcal, first quartile=719 kcal, median=748 kcal, third quartile= 778 kcal, maximum=928 kcal and mean=753 kcal.

(a)


Energy per meal (kcal)
5C-0Veg
5C-0Veg-FR
5C-4Veg
5C-4Veg-FR
Ref.
5C-8Veg
5C-8Veg-FR
5C-12Veg
5C-12Veg-FR
ns
5C-20Veg
5C-20Veg-FR**
5C-16Veg-4Fish
5C-16Veg-4Fish-FR*
5C-12Veg-4Fish-4PP
ns
5C-12Veg-4Fish-4PP-FR*

(b)


MAR (% for 2000 kcal)
5C-0Veg
5C-0Veg-FR
5C-4Veg
5C-4Veg-FR
Ref.
5C-8Veg
5C-8Veg-FR
5C-12Veg
5C-12Veg-FR
5C-20Veg
5C-20Veg-FR**
5C-16Veg-4Fish
5C-16Veg-4Fish-FR*
5C-12Veg-4Fish-4PP
5C-12Veg-4Fish-4PP-FR*

(c)

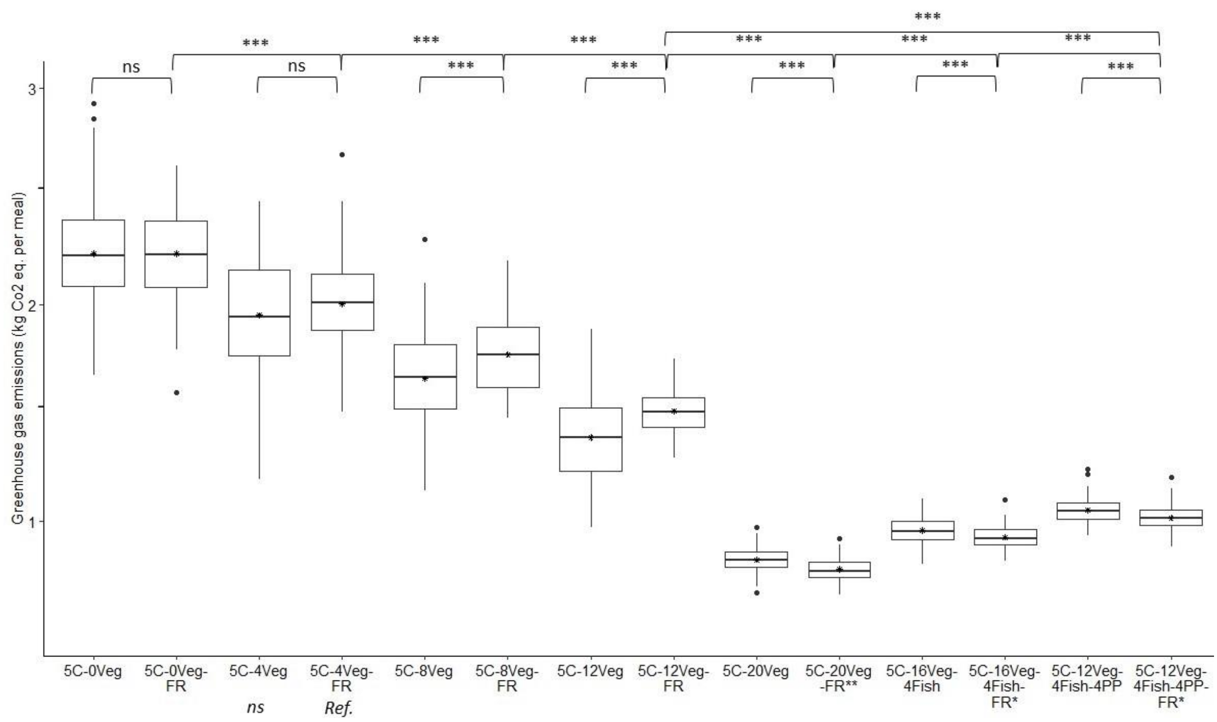
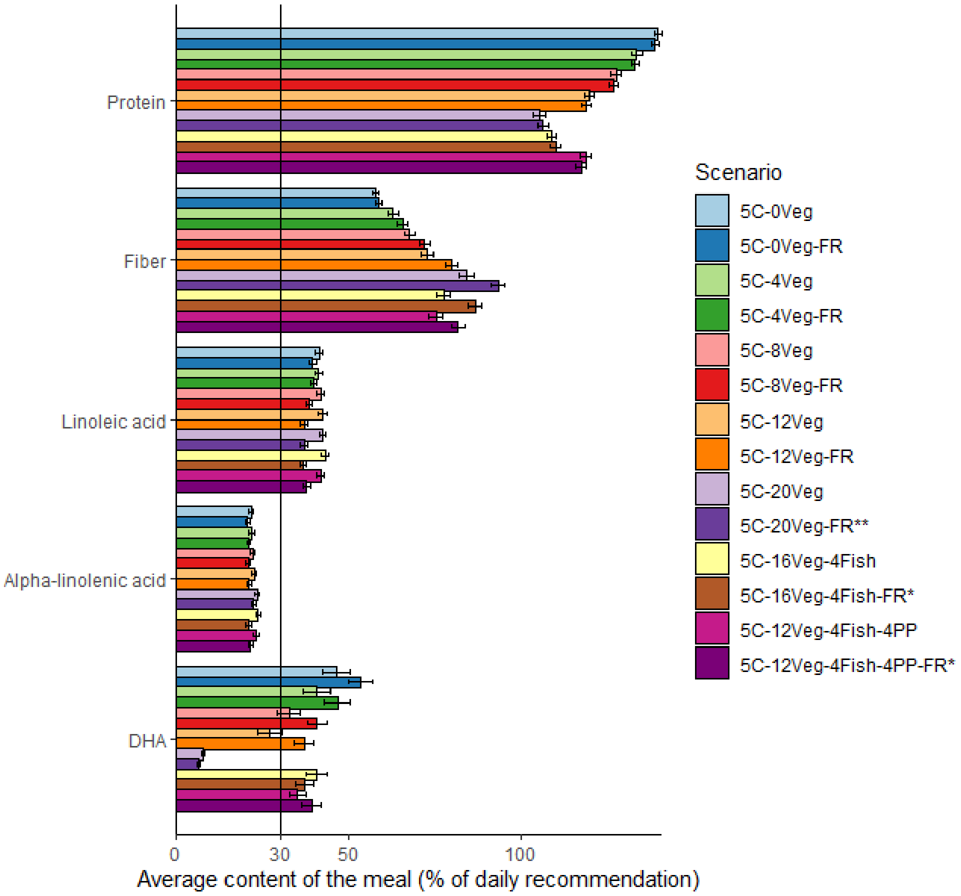


Fig. 2 a) Energy per meal (kcal); **b)** Mean Adequacy Ratio (MAR) (% for 2000 kcal) and **c)** Greenhouse gas Emissions (GHGE) (kg CO_2 eq. per meal), in the series of 20 meals (n=100) generated with the five component (5C) scenarios. Energy, MAR, and GHGE were compared between two scenarios using t-test. '***' p-value <0.001 '**' p-value <0.01 '*' p-value <0.05 'Ref.': Reference scenario. 'ns': not significant. All the scenarios were significantly different from the reference scenario (5C-4Veg-FR) except the ones labeled *ns*.

(a)


Protein
Fiber
Linoleic acid
Alpha-linolenic acid
DHA
0
30
50
100
Average content of the meal (% of daily recommendation)
Scenario
5C-0Veg
5C-0Veg-FR
5C-4Veg
5C-4Veg-FR
5C-8Veg
5C-8Veg-FR
5C-12Veg
5C-12Veg-FR
5C-20Veg
5C-20Veg-FR**
5C-16Veg-4Fish
5C-16Veg-4Fish-FR*
5C-12Veg-4Fish-4PP
5C-12Veg-4Fish-4PP-FR*

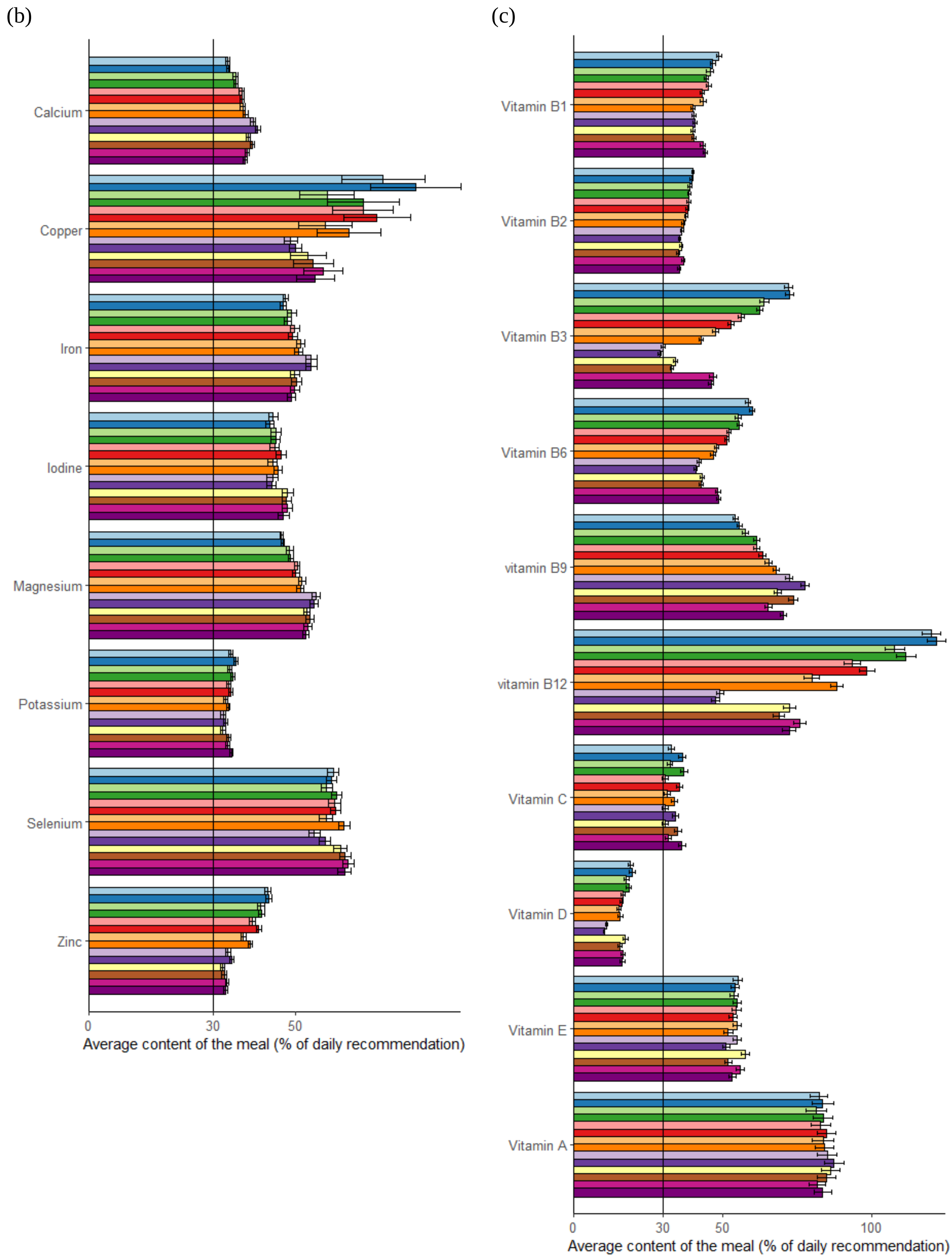


Fig. 3 a) Protein, fiber, and omega 3 fatty acid; **b)** mineral and **c)** vitamin content of meals, in the series of 20 meals (n=100) generated with the five components (5C) scenarios, expressed as percentage of the daily recommendation per meal. The error bars represent the confidence intervals.

Table 2. Environmental impacts (acidification, greenhouse gas emissions (GHGE), water use, fossil resource use, freshwater eutrophication, marine eutrophication, and land use) of meals, in the series of 20 meals (n=100) generated with the five component (5C) scenarios, average values expressed per meal and as percentage of the 5C-4Veg-FR reference scenario.

Scenario	**Acidification**	**GHGE**	**Water use**	**Fossil resources use**	**Freshwater eutrophica-tion,**	**Marine eutrophica-tion**	**Land use**
5C-0Veg	+13.6*%	+11.6*%	-4.28*%	+10.2*%	+5.92%	+10.3*%	+13.5*%
5C-0Veg-FR	+13.5*%	+11.6*%	+5.21*%	+8.84*%	+11.2*%	+10.2*%	+12.3*%
5C-4Veg	-3.42*%	-2.59%	-9.17*%	+0.245%	-2.95%	-3.6*%	-1.99%
<u>5C-4Veg-FR</u>	0.027 mol H^+ eq.	2.00 kg CO_2 eq.	1.74 m^3 world eq	18.1 MJ	0.29 kg P eq.	8.21 kg N eq.	104 points
5C-8Veg	-19.1*%	-17.2*%	-14.9*%	-8.41*%	-12.2*%	-16.4*%	-16.3*%
5C-8Veg-FR	-13.1*%	-11.7*%	-2.22%	-7.69*%	-12.4*%	-11.1*%	-12.5*%
5C-12Veg	-35.1*%	-30.8*%	-17.3*%	-16.6*%	-20*%	-29.6*%	-30.9*%
5C-12Veg-FR	-27.6*%	-24.7*%	-10.4*%	-17.5*%	-18.2*%	-21.8*%	-24.6*%
5C-20Veg	-67.5*%	-59.1*%	-27.6*%	-36.2*%	-42.9*%	-56.3*%	-58.9*%
5C-20Veg-FR**	-69.3*%	-61.2*%	-18.5*%	-38.3*%	-44.5*%	-58.1*%	-60.8*%
5C-16Veg-4Fish	-53.6*%	-52.2*%	-22.4*%	-25.1*%	-23.6*%	-42.7*%	-59*%
5C-16Veg-4Fish-FR*	-54*%	-53.8*%	-15*%	-25.5*%	-30.1*%	-44.7*%	-61.5*%
5C-12Veg-4Fish-4PP	-46*%	-47.6*%	-20.2*%	-16.7*%	-22.6*%	-38.1*%	-54.2*%
5C-12Veg-4Fish-4PP-FR*	-47.2*%	-49.4*%	-8.77*%	-17.5*%	-17.9*%	-38.8*%	-56.*2%

For each scenario, values were compared with the '5C-4Veg-FR' reference scenario using the t-test.* indicates a statistically significant difference between the two scenarios ($p<0.05$).