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Testing the nutritional relevance of food-based dietary guidelines with mathematical optimisation of individual diets

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Abstract

Mathematical optimisation of diets is generally used to translate nutrient-based recommendations into healthy food choices but can also be used to assess the possible impact of food-based dietary guidelines (FBDG) on nutrient intakes. Optimisation of individual diets, which allows individual variability of food consumption to be taken into account, generates more robust results and more realistic diets than population diet optimisation. It was used to simulate the impact on nutrient intakes of complying with the new French FBDGs. For each observed diet of adults in the French *INCA2* survey, a new isoenergetic diet was designed to meet all food consumption frequencies recommended by the new French FBDGs, as interpreted by the constraints included in a model called DP2. Because the dairy food group is the only one whose guideline has been reduced (from 3 to 2 portions/day) compared to the previous FBDGs, an alternative model, called DP3, imposing 3 daily portions of dairy products instead of 2 was also tested. Diets optimised with the DP2 model had lower energy density and higher nutrient density than the observed diets, and inadequate intakes decreased for most vitamins and minerals. With the alternative DP3 model, the decrease in saturates was less pronounced than with 2 portions/day of dairy products (13.8%, 11.9% and 12.8% energy in observed diets and in DP2 and DP3, respectively), but calcium adequacy was improved instead of being worsened (51%, 58% and 16% of inadequacy in observed diets and in diets modelled with 2 portions/day and 3 portions/day of dairy products, respectively). Individual diet optimisation is a powerful tool for assessing the nutritional relevance of existing FBDGs and to test possible alternatives.

Keywords: calcium, dairy products, dietary recommendations, multi-criteria analysis, nutritional quality, optimisation

Introduction

Food-based dietary guidelines (FBDGs) are intended to positively influence food choices to maintain good health and help prevent chronic diseases. FBDGs are disseminated to the general public in the form of food

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guides. In accordance with the guidelines adopted at the Second International Conference on Nutrition under the auspices of the Food Administration Organization of the United Nations (FAO) and the World Health Organization (WHO) in 2014 (Joint FAO/WHO 2014), more than 100 countries have adopted a food guide (FAO 2019). Compliance with dietary recommendations promoted by these guides is intended to cover all the nutritional needs while respecting the eating habits of the population (Joint FAO/WHO Consultation 1998).

The process for the development and revision of a food guide has been documented by WHO and FAO (Joint FAO/WHO Consultation 1998) and by the European Food Safety Authority (EFSA) (EFSA NDA Panel 2010). EFSA recommends using modelling approaches to identify food choices that facilitate the coverage of nutritional needs (EFSA NDA Panel 2010). Mathematical optimisation of diets is one such approach since it is able to translate nutrients into foods, in order to find the optimal combination of foods meeting a full set of nutrient-based recommendations (Dantzig 1990). Diet optimisation has informed the elaboration of dietary guidelines in several regions where malnutrition is prevalent [*e.g.* in Africa (Ferguson *et al.* 2015; Levesque *et al.* 2015; Vossenaar *et al.* 2017), South America (FANTA 2013) and Southeast Asian countries (Ferguson *et al.* 2019)]. Its use has accelerated in the last few years with the need for multi-criteria approaches able to operationalise the complex sustainable diet concept (Gazan *et al.* 2018a). Diet optimisation has been used more rarely to simulate the fulfilment of food-based recommendations and assess their possible impacts on nutrient intakes (Ferguson *et al.* 2004; Katamay *et al.* 2007; EFSA NDA Panel 2010). In addition, the vast majority of diet optimisation studies draw their conclusions from the characteristics of only one or a few optimised diets, derived from population or sub-populations diets. Mathematical optimisation of individual diets (*i.e.* modelling each individual diet in a population sample) allows individual variability of food consumption to be taken into account. Individual diet optimisation generates, therefore, optimised diets that are more realistic than diets modelled with population diet optimisation. Individual diet optimisation is also much more powerful because it leads to a wide range of optimised diets which can be statistically analysed, providing robustness to the conclusions (Maillot *et al.* 2010).

In France, the 'Food Guide for All' (Ministère de l'emploi et de la solidarité 2001) was first distributed in 2001 as part of the first National Health and Nutrition Program (Programme National Nutrition Santé, PNNS) and had not been revised until 2017. The revision was commissioned by the French Ministry of Health to the French Public Health Agency (called Public Health France, PHF), which drew up the operational messages, based on several elements including the following: a report of the French Food Safety Agency (ANSES 2016c); a report of the High Council for Public Health (HCSP 2017); a collective expertise on food and diet communication (Expertise collective INSERM 2017); and specific consultations and surveys conducted with experts, professionals and consumers, particularly from low-income populations (Santé Publique France 2017). Compared to previous FBDGs, in the 2017 guidelines, the changes are as follows: (1) the addition of messages on food categories that were not previously the subject of specific recommendations (pulses, deli meats, nuts, wholegrain products), (2) a clarification of messages on fats (promotion of rapeseed, walnut and olive oils) and meats (distinction between poultry and 'meat except poultry') and (3) a decrease in the recommended frequency for dairy products from 3 to 2 portions/day (HCSP 2017). Dairy products are the only group for which the recommended frequency has been reduced compared to the previous French FBDGs. However, dairy is by far the largest contributor to calcium intakes in the French population (ANSES 2017). This raises the question of what impact decreasing the recommended frequency of intake of dairy products has on the adequacy of calcium intakes.

The objective of this study was to use individual diet optimisation to test the impact on the nutrient intakes of French adults of fulfilling the newly released national FBDGs. An alternative option with one additional portion of dairy products per day (*i.e.* as in the previous FBDGs) was also tested.

Materials and methods

Food consumption data and nutrient composition

Data from the dietary survey *INCA2* conducted in 2006-2007 on a representative sample of the French population (Dubuisson *et al.* 2010) were used for this study. In terms of ethics of human subject participation, this survey was approved by the CNIL, the French Data Protection Authority (CNIL: 'Commission Nationale Informatique et Libertés' No. 2003X727AU) and the CNIS, the French National Council for Statistical Information (CNIS: 'Conseil National de l'Information Statistique'). Verbal informed consent was obtained from all participants and formally recorded. Participants completed a food diary for 7 consecutive days. After exclusion of under-reporters identified using Black equations (Black 2000), only data from adults aged 18 years and over having reported all 7 days were kept. The final sample contained 1863 individuals which reported, as a whole, the consumption of 1300 foods. Since FBDGs deliver recommendations on relatively broad categories of foods and not on specific foods, and since our aim was to simulate the fulfilment of FBDGs, we decided to work with a short food database of food items, named the SUSTABLE database (Gazan *et al.* 2018b), which provides the nutritional composition of 206 food composite items commonly consumed in France. As previously described (Gazan *et al.* 2018b), each food declared as consumed in the *INCA2* survey was linked with one food item in the SUSTABLE database, and the nutrient content of each food item in the SUSTABLE database was the average nutrient content of one or several related foods in the *INCA2* food database, weighted by the level of intakes of the related foods in the population. The 206 composite items were grouped into 55 categories, 27 subgroups and 8 groups (fruit and vegetables, grains and starches, meat/fish/eggs, dairy, mixed dishes, sweetened products, beverages including water, and added fats). This first nomenclature into groups and subgroups covers all the reported foods. A second nomenclature covering only those foods for which there is a specific recommendation in the new French FBDGs was used for this study. In this case, reference will be made to PHF groups and subgroups, such as fruit and vegetables (not including pulses), nuts, wholegrain products, pulses, poultry, other meats, deli meat, cooked ham, soft drinks, fruit juices, animal fats (butter and cream), vegetable oils to be promoted (rapeseed, walnut and olive oils) and dairy products (milk, yogurt, cheese). Dairy products were counted in portions, using the quantities indicated in the report from PHF (Santé Publique France 2017), namely 150 ml of milk, 125 g of yogurt and 30 g of cheese. The two nomenclatures do not therefore necessarily overlap. For example, in the SUSTABLE nomenclature, the 'beverages' group includes the subgroups water, tea/coffee/infusions, soft drinks, fruit juices and alcoholic beverages, while in the PHF nomenclature, there is no beverage group, but a subgroup 'soft drinks (including fruit juices)' within the group 'sweet products and drinks'. All food items containing at least two PHF groups were disaggregated. For example, a baguette-salad-cheese sandwich was broken into three PHF groups, namely refined grains, fruit and vegetables and dairy. Similarly, cheese or milk included in mixed dishes was, respectively, recorded in the total quantity of cheese and milk, as recommended by PHF.

Modelling diets to simulate the fulfilment of the new French food-based dietary guidelines

Individual diet modelling was developed by Maillot *et al.* (2010). This approach is applicable to a sample of individuals for whom food consumption is known over several days (observed diets). The principle is to apply linear programming to model a new diet (called the modelled diet or the optimised diet), which respects a set of constraints for each individual in the sample, while staying as close as possible to its original observed diet. In a linear programming model, the variables are the amounts of foods that the model can change to meet a set of constraints on nutrients and/or foods (*e.g.* ranges of recommended amounts of foods or food groups).

In this study, individual diet modelling (Maillot *et al.* 2010) was applied to obtain two modelled diets for each observed diet (*i.e.* dietary intakes reported by each *INCA2* adult participant), one meeting the new French FBDGs, namely all the recommended frequencies including the 2 portions of dairy products per day (DP2 model), and an alternative model with one additional portion of dairy products (DP3 model). In both models, the energy content of each modelled diet was constrained to being equal to the observed intake ($\pm 1\%$), but no other constraint was imposed on nutrients (except sodium, see below). The objective function was defined as the difference between the observed diet and the modelled diet, and this difference was minimised in order to obtain a modelled diet as close as possible to the observed diet. The detail of the objective function has been published previously (Maillot *et al.* 2010; Lluch *et al.* 2017).

Interpreting the new French food-based dietary guidelines into mathematical constraints on Public Health France food groups and subgroups

To simulate the fulfilment of the new French FBDGs in modelled diets, constraints on PHF food groups and subgroups were introduced into the models. The original guidelines and their interpretation into mathematical constraints are listed in Table 1. For most PHF food groups and subgroups, such as fruit and vegetables, nuts, pulses, dairy products and fish (fatty and not fatty), the guidelines are already quantified and they have therefore been directly transformed into quantified constraints in the models.

Table 1 List of constraints on energy, sodium and quantities of PHF (Public Health France) food groups and subgroups used to simulate the fulfilment of French food-based dietary guidelines [as defined in HCSP (2017)] with individual diet optimisation models

PHF food groups and subgroups	Constraints	Official guidelines
Energy and sodium		
Energy kcal/day	= ±1% the observed intake	
Sodium mg/day	≤2273 mg/day for women and <2994 mg/day for men, and, for individuals having intakes lower than these thresholds: ≤ the observed intake	Reduce salt intake
Fruit and vegetables*		
Total fruit and vegetables, g/day	≥400 g/day	At least five a day. Recommended serving sizes are 80–100 g
Fruit and vegetables, portions/week	Addition of at least 1 portion/week	It is recommended to increase fruit and vegetable consumption, regardless of the initial level of consumption
Nuts without salt, g/day	= 15 g/day	A small handful per day
Grains†		
Total grain products, g/day	No constraint	To be consumed every day
Wholegrain products, g/day	≥66.6% of total grain products	Favour whole or unrefined products over refined products
Refined grains, g/day	<33.4% of total grain products	Favour whole or unrefined products over refined products
Pulses‡		
Pulses, g/day	≥57 g/day	At least twice a week
Meat and deli meat		
Total meat, g/day	≤ the observed intake	Limit the consumption of red meat (defined as all meats except poultry) and favour the consumption of poultry
Meat except poultry, g/day	<50% of total meat, and <71 g/day (equivalent to 500 g/week)	For those who like red meat: limit its consumption to a maximum of 500 g per week
Poultry, g/day	≥ 50% of total meat	Limit the consumption of red meat and favour the consumption of poultry
Deli meat (including cooked ham), g/day	≤ the observed intake, or, for individuals having an observed intake >150 g/week: <21 g/day (equivalent to 150 g/week)	Limit the consumption of deli meat. For those who like deli meat: limit its consumption to a maximum of 150 g per week
Cooked ham, g/day	≥ 50% of total deli meats	Within deli meat, give preference to cooked ham
Fish and seafood		
Total fish and seafood, g/day	= 29 g/day (eq. 200 g/week)	Twice a week, including 1 fatty fish
Fatty fish, g/day	= 50% of total fish and seafood	Twice a week, including 1 fatty fish
Dairy		
Total dairy products, p/day	= 2 p/day in DP2 model; = 3 p/day in DP3 model	Current guideline: 2 dairy products per day. Previous guideline: 3 dairy products per day
Milk, portion of 150 ml	≤2 p/day in DP2 model; ≤3 p/day in DP3 model	Recommended serving size for milk: 150 ml
Yogurt, portion of 125 g	≤2 p/day in DP2 model; ≤3 p/day in DP3 model	Recommended serving size for yogurt: 125 g
Cheese, portion of 30 g	≤2 p/day in DP2 model; ≤3 p/day in DP3 model	Recommended serving size for cheese: 30 g
Sweet products and drinks		
Total sweet products and drinks, g/day	≤ the observed intake	Limit the consumption of sweet products and drinks
Soft drinks (including fruit juices), g/day	≤ the observed intake or, for individuals having an observed intake >150 ml/day: <150 ml/day	Limit the consumption of sweet and sweet-tasting drinks: their consumption must remain exceptional, and for consumers, be limited to one glass a day
Fruit juices*, g/day	≥50% of 'soft drinks (including fruit juices)'	No more than one glass of fruit juice per day, which within this limit can count as one serving of fruit and vegetables
Added fats		
Total added fats, g/day	≤ the observed amount, or, for individuals having an observed intake greater than the 3rd quartile: ≤3rd quartile	Avoid excess consumption
Animal fats, g/day	≤ the observed intake	Animal fats must be consumed raw or as spreadable product, and in limited quantities
Vegetable fats, g/day	no constraint	

Table 1 *Continued*

PHF food groups and subgroups	Constraints	Official guidelines
Vegetable oils to favour[§], g/day	≥50% of total added fats (animal fats and vegetable fats)	Favour rapeseed and nut oil (rich in ALA) and olive oil without increasing the usual amount of added fats

ALA, alpha-linolenic acid; p, portions.

*The quantities of fruit juices are recorded in both the PHF group 'fruit and vegetables' and in the PHF group 'soft drinks (including fruit juices)'.

[†]The only breakfast cereals that can be included in this group are unsweetened breakfast cereals.

[‡]Pulses are not part of fruits and vegetables.

[§]Correspond to rapeseed oil, walnut oil and olive oil.

Other guidelines recommend limiting the consumption of some PHF groups, such as meat (except poultry), deli meats, sweet products, soft drinks and total fats, without quantifying this reduction. Such guidelines have been interpreted as a constraint imposing that the food group is not increased in the modelled diet compared to the amount present in the observed diet. For meat and deli meats, a reduction was imposed when the quantities consumed were above the recommended maximum limits (500 and 150 g/week for meat other than poultry and deli meats, respectively), and a non-increase was imposed when these limits were not exceeded. In line with the guideline on soft drinks (including fruit juices), a constraint limiting this PHF group to one portion per day maximum was introduced, meaning that individuals with more than one portion per day will see a decrease of the total amount of soft drink (including fruit juices) in their modelled diets. For total added fats, to comply with the guideline to avoid excess fat, a constraint limiting the amount of total added fats to the third quartile of the observed distribution was imposed.

For guidelines which advise people to favour certain PHF subgroups within the broader PHF group, it was considered that the subgroup should represent at least 50% of the total amount of the group: poultry in total meats, cooked ham in total deli meat, fruit juices in total soft drinks and recommended oils (rapeseed, walnut and olive oils) in total added fats (animal fats and vegetable fats). For the guideline to prefer wholegrain products, it was considered that at least two-thirds of total grain products should be wholegrain products. The guideline to 'reduce salt intake' was interpreted as a constraint on sodium, that is the amount of sodium should not exceed the median sodium intakes in the observed diets, namely 2273 mg/day for women and 2994 mg/day for men (ANSES 2016c), and should not exceed the observed intake for individuals having intakes lower than these thresholds.

The only difference between the DP2 and DP3 models was the constraint on dairy products: starting from an average consumption of 2.6 portions/day (including those present as ingredients in mixed dishes) in the observed diets, this frequency was set at 2 portions/day and 3 portions/day by DP2 and DP3 models, respectively. In other words, both the DP2 and DP3 models led to modelled diets that were isocaloric with the corresponding observed diets and that fulfilled all the above-described constraints on PHF food groups and subgroups, with the DP3 model imposing one additional portion per day of dairy products compared to the DP2 model.

Acceptability constraints

The theoretical acceptability of the modelled diets was maintained by constraints limiting: (1) the caloric total weight (sum of weight of foods whose energy density is at least 5 kcal/100 g) to 120% of the weight of the observed diet; (2) the amount per food group to the 95th percentile (calculated in the total population); and (3) the amount of each food subgroup and each food item to the 97.5th percentile (calculated among consumers of the food subgroup or the food item considered). These constraints aimed to ensure that the optimised diets did not meet the FBDGs constraints by introducing unacceptable increases or decreases in particular foods or food subgroups.

Statistical analysis

The nutrient content of the observed and modelled diets was estimated for about 30 nutrients including macronutrients, essential fatty acids, fibre, vitamins and minerals. Nutritional quality was estimated with three indicators: the energy density, expressed in kcal/100 g and calculated excluding liquid foods such as milk and beverages, as previously recommended (Ledikwe *et al.* 2005), the MAR (Mean Adequacy

Ratio, expressed in percentage of overall nutritional adequacy per day) (Guthrie & Scheer 1981) based on 23 nutrients and the MER (Mean Excess Ratio, expressed in percentage excess per day) (Vieux *et al.* 2013) based on saturates, sodium and free sugars. The lower the energy density and the MER, and the higher the MAR, the better the nutritional quality of the diet.

The percentage of inadequacy to the nutritional recommendation was calculated for each nutrient. Under the assumption of a Gaussian distribution of nutritional requirements in a given population, the estimated average requirement (EAR) is the value for which it is assumed that half of the individuals in the population are meeting their needs. When there is insufficient data to estimate the distribution of individual needs (and therefore the EAR) for a nutrient, the recommended value, called Adequate Intake (AI), is the average daily intake of a population (or subgroup) for which the nutritional status is considered satisfactory. For each nutrient, the percentage of inadequacy compared to the nutritional recommendation was obtained by calculating the percentage of diets not reaching, either the AI (for thiamin, riboflavin, vitamin B6, vitamin B12, magnesium, phosphorus, selenium, iodine, essential fatty acids and fibre) or the EAR (for the other nutrients) (Carriquiry 1999). The nutritional recommendations (*i.e.* the AI and EAR values) used by the French Food Safety Agency in their report providing the scientific basis for the development of the new FBDGs were also used to calculate the MAR and the MER (ANSES 2016a). The quantities of the PHF groups, the nutritional characteristics of the diets and the percentages of inadequacy to the nutritional recommendations were compared between observed and DP2 and DP3 modelled diets using paired tests based on a general linear model adjusted for energy, gender and age. The SAS 9.4 software was used to conduct Individual diet optimisation models and statistical analyses. It was possible to optimise diets (*i.e.* simultaneous compliance with all the constraints was mathematically achievable) with both the DP2 and DP3 models for a total of 1847 individuals, representing more than 98% of the sample.

Results

Impact of complying with the new French food-based dietary guidelines (as interpreted by the optimisation models) on the food content of diets

The DP2 model induced an increase in the quantities of fruits, vegetables, nuts, wholegrain products and vegetable fats in the modelled diets compared to the observed diets (Table 2). In parallel, the DP2 model reduced the quantities of refined grains, total meat, mixed meat dishes, dairy products (milk being halved), dairy desserts, pies, cakes and Viennese pastries, soft drinks, fruit juices, animal fats and, to a lesser extent, seafood products (4 g/day reduction on average). Similar variations were observed between the observed diets and DP3 modelled diets, except, by intention, for the dairy group: the amount of milk remained stable while yogurts and cheese increased (+43 and +13 g/day, respectively). Both models induced an increase in the proportion (by weight) of food of plant origin (including as ingredients) from 76.3% in the observed diets to 82.2% and 78.5% with DP2 and DP3, respectively.

Impact of complying with the new French food-based dietary guidelines (as interpreted by the optimisation models) on indicators of overall nutritional quality

The DP2 model improved the overall nutritional quality of diets, as shown by the improvement of the energy density, the MER and the MAR after the optimisation process (Table 3). The same trends of improvement were achieved with the DP3 model. Compared to the observed diets, the energy density of the modelled diets was reduced by an average of 32 kcal/100 g with both the DP2 and DP3 models. In addition, the MER was reduced and the MAR was increased with both models compared to the observed diets (MER: 17.7, 6.8 and 7.9% excess; MAR: 83.9, 88.8 and 89.5% overall adequacy for observed, DP2 and DP3, respectively). However, the MAR increased more with DP3 than with DP2, and the MER decreased more with DP2 than with DP3.

Impact of complying with the new French food-based dietary guidelines (as interpreted by the optimisation models) on other characteristics of the diets

The DP2 model induced a slight but significant decrease in percentage of energy contribution from proteins while carbohydrates, free sugars and total fats remained almost stable. Oleic acid and alpha-linolenic acid (ALA), as well as saturates (total saturates and the sum 'lauric + myristic + palmitic'), improved significantly in the DP2 compared to the observed diets (*i.e.* oleic acid and ALA contents increased and saturates decreased). However, linoleic acid (LA) also increased so that the LA/ALA ratio only slightly improved, decreasing from an average 11.4 in the

Table 2 Means and standard deviations of quantities (g/day) of food subgroups (SUSTABLE nomenclature) in observed diets (n = 1847) and in DP2 (n = 1847) and DP3 (n = 1847) modelled diets

	Observed diets		DP2 diets		DP3 diets		P*		
Food groups and subgroups	Mean	SD	Mean	SD	Mean	SD	Observed vs. DP2	Observed vs. DP3	DP2 vs. DP3
Fruits and vegetables									
Vegetables (including soups)	215.9	143.3	269.6	114.9	262.8	113.0	<0.001	<0.001	0.0111
Fruits (fresh and processed)	159.7	144.9	299.9	170.9	286.2	168.6	<0.001	<0.001	<0.001
Nuts and dried fruits	2.9	7.1	16.6	5.4	16.5	5.2	<0.001	<0.001	0.4152
Grains and starches									
Refined grains	161.7	97.1	79.7	43.9	73.4	44.2	<0.001	<0.001	<0.001
Unrefined starches†	77.2	59.6	219.5	91.0	206.0	91.1	<0.001	<0.001	<0.001
Breakfast cereals	4.8	15.5	5.1	16.7	4.9	16.2	<0.001	0.0107	0.2096
Meat/fish/eggs									
Eggs	14.7	17.2	22.5	24.4	20.8	23.3	<0.001	<0.001	<0.001
Fish and sea products	32.4	30.7	28.1	2.5	28.2	2.3	<0.001	<0.001	0.8461
Meats and deli meat	113.9	62.8	86.4	50.5	84.1	50.6	<0.001	<0.001	0.0017
Plant-based substitutes for meat	1.4	5.4	3.2	9.0	2.9	8.5	<0.001	<0.001	0.0713
Mixed dishes									
Mixed meat dishes	91.5	82.6	62.2	54.8	60.2	53.1	<0.001	<0.001	0.1903
Mixed dishes without meat	32.2	48.1	29.6	37.1	27.6	35.0	0.0255	<0.001	0.0051
Dairy									
Milk	90.2	140.2	45.5	67.2	90.1	109.7	<0.001	0.9595	<0.001
Yogurts	80.3	80.1	79.2	66.7	112.3	90.6	0.153	<0.001	<0.001
Cheese	33.3	28.0	28.3	17.0	41.3	24.2	<0.001	<0.001	<0.001
Sweetened products									
Pies, cakes and Viennese pastries	65.2	53.6	60.4	50.1	59.4	49.2	<0.001	<0.001	0.0310
Cookies, candies, chocolate	36.5	35.3	41.8	39.1	40.9	38.4	<0.001	<0.001	0.0062
Dairy desserts	17.8	32.6	15.1	27.4	15.3	27.5	<0.001	<0.001	0.2145
Plant-based substitutes for dairy desserts	5.0	29.9	17.2	62.2	12.5	50.1	<0.001	<0.001	<0.001
Beverages									
Water	771.7	562.8	1074.4	706.1	1056.4	704.2	<0.001	<0.001	0.1318
Tea, coffee	405.7	345.4	405.5	345.3	405.5	345.3	0.4879	0.4879	1
Soft drinks	62.6	156.5	12.8	23.7	12.6	23.6	<0.001	<0.001	0.9478
Fruit juices	56.3	88.4	47.0	52.3	46.5	52.2	<0.001	<0.001	0.5652
Alcoholic beverages	139.8	201.0	139.8	201.0	139.8	201.0	<0.001	<0.001	<0.001
Added fats									
Animal added fats	13.6	13.4	5.4	5.1	5.3	5.1	<0.001	<0.001	0.9664
Vegetable added fats	23.2	16.5	27.0	16.2	25.8	15.7	<0.001	<0.001	<0.001
Seasonings	8.4	11.1	7.4	9.7	7.0	9.3	<0.001	<0.001	0.0438
Plant share, % of total weight	76.3	9.4	82.2	5.7	78.5	6.9	<0.001	<0.001	<0.001

*P values after adjustment for energy intake, gender and age.
†In the SUSTABLE nomenclature, the subgroup 'unrefined starches' includes wholegrain products, potatoes and pulses.

observed diets to 9.5 in the DP2 modelled diets. For long-chain omega-3 fatty acids (EPA + DHA), although the mean level increased compared to the observed diets (0.24 and 0.30 g/day in the observed and DP2 modelled diets, respectively), the percentage of inadequacy, already high in the observed diets, was increased: 88% and 98% of inadequacy in observed and DP2 modelled diets, respectively. For fibre, the mean level increased (18.5 and 24.8 g/day in observed and DP2 modelled diets, respectively), but the percentage of inadequacy compared to recommendations, already high in the observed diets, was only slightly improved: 95% and 81% of inadequacy in observed and DP2 modelled diets, respectively.

Compared to the observed diets, the DP2 model improved the situation for most vitamins and minerals (Fig. 1). Vitamins C, B6 and folate were the most impacted, with an improvement in their percentages of inadequacy by a factor of 2, 3 and 4, respectively. The percentages of inadequacy were also improved for

Table 3 Characteristics (means and standard deviations, SD) of the observed diets (n = 847) and the corresponding DP2 (n = 1847) and DP3 (n = 1847) modelled diets

	Observed diets		DP2 diets		DP3 diets		P*		
	Mean	SD	Mean	SD	Mean	SD	Observed vs. DP2	Observed vs. DP3	DP2 vs. DP3
Total weight, g/day	2750.1	778.6	3175.4	772.1	3192.9	780.0	<0.0001	<0.0001	0.0041
Weight of solid foods, g/day	1094.5	308.6	1336.1	334.9	1323.5	339.3	<0.0001	<0.0001	<0.0001
Weight of liquids, g/day	1655.6	652.3	1839.2	736.0	1869.4	746.9	<0.0001	<0.0001	<0.0001
Energy density† kcal/100 g	183.0	31.1	151.4	20.1	151.3	20.2	<0.0001	<0.0001	0.2220
MAR, % adequacy/day	83.9	7.3	88.8	4.8	89.5	4.6	<0.0001	<0.0001	<0.0001
MER, % excess/day	17.7	14.3	6.8	9.0	7.9	9.0	<0.0001	<0.0001	<0.0001
TEEA, kcal/day	2221	594	2213	582	2215	582	<0.0001	<0.0001	<0.0001
Protein, %TEEA	15.9	2.6	15.0	2.5	15.6	2.6	<0.0001	<0.0001	<0.0001
Total carbohydrates, %TEEA	42.1	6.3	42.0	5.8	40.7	6	0.0146	<0.0001	<0.0001
Total sugars, %TEEA	16.3	5.2	18.7	4.8	18.9	4.9	<0.0001	<0.0001	<0.0001
Sodium, mg/day	3333.0	1017.1	2466.9	414.2	2466.9	411.7	<0.0001	<0.0001	0.9972
Free sugars‡, %TEEA	9.6	4.8	9.4	4.1	9.4	4.1	0.0401	0.0059	0.1663
Fibre, g/day	18.5	5.6	24.8	5.9	23.8	5.8	<0.0001	<0.0001	<0.0001
Total fat, %TEEA	36.3	5.4	36.6	5.1	37.4	5.2	0.0082	<0.0001	<0.0001
Oleic acid, %TEEA	10.5	2.6	12.0	2.4	11.9	2.4	<0.0001	<0.0001	<0.0001
Polyunsaturated fatty acids, %TEEA	5.5	1.8	6.1	1.3	5.9	1.2	<0.0001	<0.0001	<0.0001
Linoleic acid (LA), %TEEA	4.9	1.8	5.4	1.2	5.2	1.1	<0.0001	<0.0001	<0.0001
Alpha-linolenic acid (ALA), %TEEA	0.45	0.16	0.57	0.16	0.57	0.15	<0.0001	<0.0001	<0.0001
EPA + DHA, g/day	0.24	0.21	0.30	0.07	0.30	0.07	<0.0001	<0.0001	0.1714
LA/ALA	11.4	4.8	9.7	2.3	9.5	2.2	<0.0001	<0.0001	<0.0001
Total saturated fatty acids, %TEEA	13.8	2.7	11.9	2.0	12.8	2.2	<0.0001	<0.0001	<0.0001
Lauric+myristic+palmitic saturated fatty acids, %TEEA	9.0	1.7	7.9	1.3	8.6	1.4	<0.0001	<0.0001	<0.0001

MAR, mean adequacy ratio; MER, mean excess ratio; TEEA, total energy excluding alcohol.
*P values after adjustment for energy intake, gender and age.
†Calculated after exclusion of milk and drinks.
‡Free sugars are added sugars and naturally occurring sugars in honey, syrups, juices and fruit concentrates (WHO 2003).

selenium and copper, but more moderately than for other nutrients. However, the DP2 model increased the percentages of inadequacy for vitamin A (from 16% to 20% in observed and modelled diets), riboflavin (from 38% to 46%), vitamin B12 (from 31% to 58%), calcium (from 51% to 58%), zinc (from 16% to 25%) and for iodine (from 78% to 86%) for which the prevalence of inadequacy was already very high in the observed diets.

Overall, the same trends were obtained with the DP3 model as with the DP2 model, although some differences occurred. Compared to the observed levels, proteins decreased to a lesser extent in DP3 than in DP2 diets. Carbohydrates slightly decreased in DP3 diets, while they remained stable in DP2 diets. The decrease in saturates was less pronounced with the DP3 model (13.8%, 11.9% and 12.8% for total saturates; 9.0%, 7.9% and 8.5% for 'lauric + myristic + palmitic' in the observed, DP2 and DP3 diets, respectively). For EPA + DHA, fibre and iodine, the percentages of inadequacy were still very high in DP3 diets (98%, 85% and 80% of inadequacy in DP3 diets for EPA + DHA, iodine and fibre, respectively), as they were high in observed and DP2 modelled diets. The main difference between the two models was noticed for calcium: while the DP2 model worsened the situation (51% and 58% of inadequacy in the observed and DP2 diets, respectively), the DP3 model significantly improved it (only 16% of inadequacy).

Discussion

This study is the first one to use the highly sophisticated method of Individual diet optimisation to check the strength and weaknesses of existing official FBDGs. The results show that complying with the new French FBDGs, as interpreted by the constraints included in the optimisation models, would improve

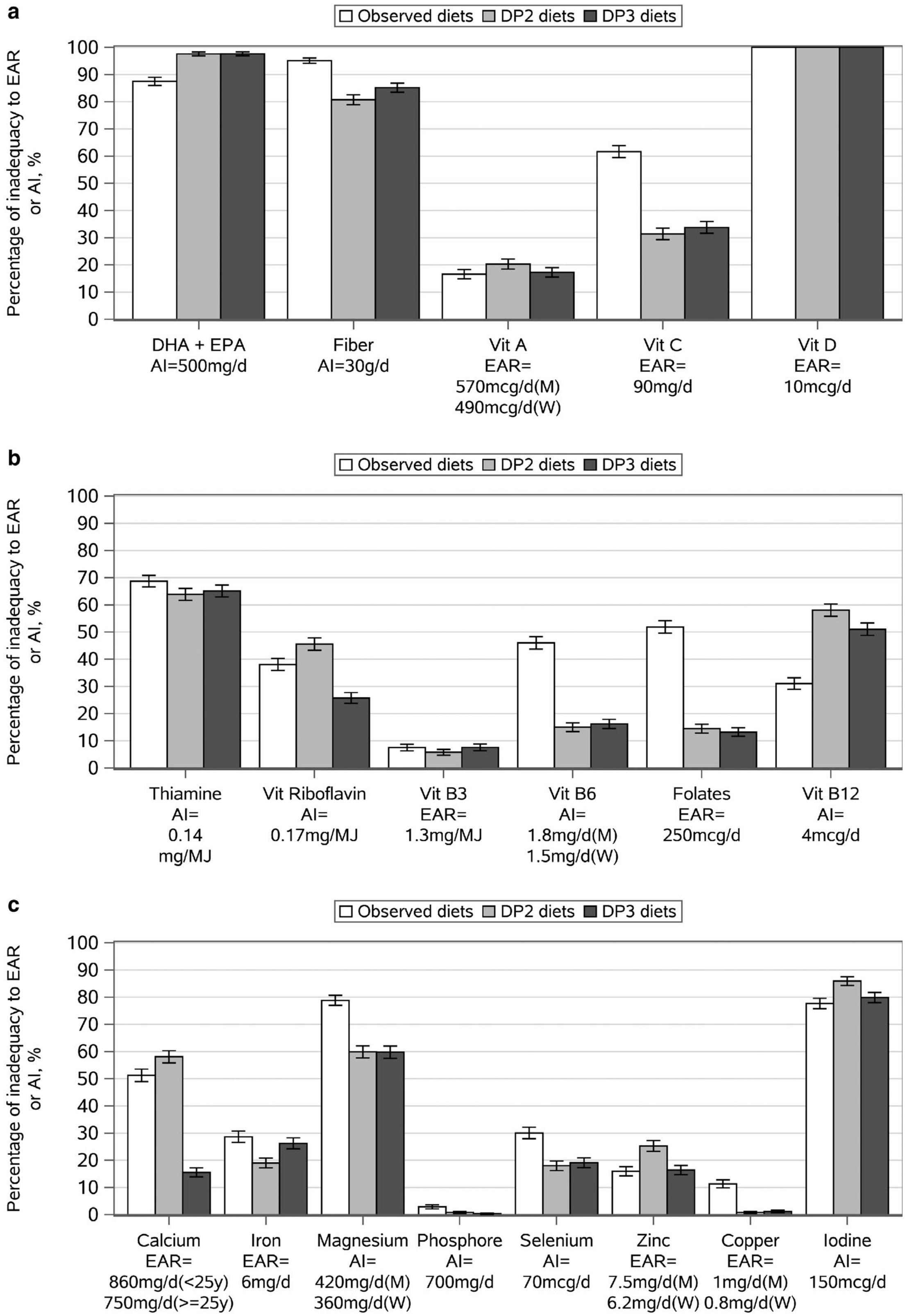

Figure 1 Percentages of inadequacy compared to the recommendations [Estimated Average Requirement (EAR) or Adequate Intake (AI)] in the observed diets (n = 1847) and in the corresponding DP2 (n = 1847) and DP3 (n = 1847) modelled diets. (a) long-chain omega-3 fatty acids (EPA + DHA), fibre, vitamins A, C and D; (b) B vitamins; (c) minerals.

the nutritional quality of individual diets, as shown by the increase in MAR, and the decrease in MER and energy density. The improvement was noticed regardless of the model used, the one imposing all currently recommended consumption frequencies including 2 portions/day of dairy products (DP2) and the one imposing one additional portion per day of dairy products, as in the previous guidelines (DP3). With the DP2 model, the improvements particularly concerned nutrients whose intakes should be limited (the MER decreased more with DP2 than with DP3, due to a greater decrease in saturates). In contrast, with the DP3 model, the improvements mainly concerned essential nutrients (the MAR increased more with DP3 than with DP2, due to calcium, zinc, iodine and riboflavin contents being more in line with nutritional recommendations in DP3 than in DP2 diets). The most important difference between the two models was for calcium: the DP2 model worsened the situation (51% of inadequacy in the observed and 58% with DP2) while the model DP3 improved it considerably (only 16% inadequacy).

Although dietary guidelines are intended to cover recommended nutrient intakes, this ability is rarely formally analysed. To our knowledge, only Canada has tested the nutritional implications of fulfilling their dietary guidelines, during their development in 2007 (Katamay *et al.* 2007). Yet, such an approach is very well suited for identifying the nutritional strengths and weaknesses of dietary guidelines. In France, the feasibility of compliance with nutrient-based recommendations (but not with FBDGs) has been regularly tested. The first nutrient-based recommendations for the French population, developed in 1992, were tested by population diet optimisation in 1999 and the results revealed their lack of internal coherence (Darmon & Briend 1999). They were therefore revised (in 2001) and population diet optimisation was again used to check their feasibility and to analyse their implications in terms of cost and food choices (Martin 2001). More recently, as part of the elaboration of the new FBDGs, the French Food Safety Agency used population diet optimisation to test the feasibility of meeting a set of nutritional constraints (the same as those used in this study to assess the nutritional adequacy of observed and modelled diets), as well as their compatibility with toxicological constraints (ANSES 2016d). The results of these optimisations were part of the scientific evidence provided by the French Food Safety Agency to guide the development, by the High Council of Public Health and PHF, of the new FBDGs tested in this study.

In its report on the revision of the French FBDGs, the French Food Safety Agency did not issue any recommendation for dairy products, but the most realistic optimised diets presented in that report contained 3.7 to 4.3 portions/day of dairy products (ANSES 2016d). Most of the other models tested by the French Food Safety Agency were infeasible or, when feasible, led to unrealistic diets: for example, the total absence of bread (whether white or wholegrain), a considerable increase in all meat, fish and eggs, or no decrease in deli meats, dairy desserts or sweet products. Such selection, which appears nutritionally irrelevant, actually reflected the abnormally high strength of some of the nutritional constraints introduced in the models. In particular, the Agency acknowledged that the high level of EPA + DHA required in the models was a problem, but the constraint was not relaxed.

The present study shows that, whatever the model (DP2 and DP3), compliance with all the new French FBDGs would not provide the recommended levels of EPA + DHA, vitamin B12 and fibre for a significant percentage of the population. This suggests either that the recommended intakes for these nutrients are too high, or that there is an incompatibility between some dietary guidelines, as interpreted in the models, and some nutrient recommendations. Thus, according to our results, compliance with the new FBDGs would reduce the percentage of adequacy to the recommendation for EPA + DHA and for vitamin B12. For EPA + DHA, this is explained by the fact that consuming exactly 2 portions of fish per week would increase the EPA + DHA intakes of low fish consumers, but would reduce those of high consumers. Not consuming more than 2 portions of fish per week is justified to tackle contaminant exposure (Leblanc *et al.* 2009), but does not seem to be compatible with the French recommended level of intakes of EPA + DHA. It would therefore be necessary either to consider EPA + DHA supplementation more systematically, as is the case for vitamin D, or to reconsider the appropriateness of the amount of EPA + DHA recommended in France (500 mg/day), given that both WHO (WHO 2003) and EFSA (EFSA NDA Panel 2010) recommend a value half as much (250 mg/day). Regarding iodine, the prevalence of inadequate intakes, very high in the observed diets, would not be reduced by compliance with the FBDGs, even with 3 portions of dairy products per day. Given that there is a specific question about the use of iodised salt in the *INCA2* survey, the high prevalence of inadequate intakes, even in the modelled diets, suggests that iodine supplementation or fortification should be considered. Moreover, the nutritional recommendation set by ANSES (150 μg/day) is the same as that set by most other national and international bodies (ANSES 2016a), and its validity can therefore hardly be questioned. Our results also suggest that the guideline to focus on rapeseed, walnut and olive oils would mainly increase oleic acid without significantly reducing the LA/ALA ratio because the French consume more olive oil than rapeseed or walnut oil, and it is reasonable to assume that they will seek to remain close to their eating habits. Regarding vitamin B12, for which the percentage of inadequacy was 31% in the observed diets, compliance with the new FBDGs (as interpreted by the models) would actually worsen the situation for this vitamin (58% and 51% inadequacy with DP2 and DP3, respectively), because they promote a more plant-based diet. Moreover, the recommendation to favour wholegrain cereals over refined ones and the introduction of specific guidelines for pulses and nuts would substantially increase the level of fibre (on average 18.0 g/day in the observed diets and 24.8 and 23.8 g/day in DP2 and DP3 modelled diets, respectively), but the percentage of individuals with intakes above the AI (30 g/day) would remain very low (under 20%), with no significant difference between the two models. Such a failure to meet the AI for fibre occurred despite the optimised diets (regardless of the model) containing around 550 g/day of fruit and vegetables and at least 2 portions of pulses (*i.e.* 2 × 200 g) per week, and having more than two-thirds of total grain products as wholegrain products. The AI for fibre therefore seems to be difficult to achieve, unless there is an even more drastic change in the food habits than those modelled in this study to interpret the new FBDGs. The guideline on grain products ('favour whole or unrefined products over refined ones') and the guideline on nuts ('a small handful per day') could have been interpreted differently, by imposing a higher proportion of wholegrains (*e.g.* at least three-quarters instead of at least two-thirds) and a greater portion of nuts (*e.g.* 30 g instead of 15 g), but we felt that that would be unrealistic.

Regarding calcium, the results show that adequacy would be much higher with 3 portions/day of dairy products (previous FBDGs) instead of 2 portions/day (new FBDGs). The choice of a frequency of 2 portions/day has not been explained in any of the above-mentioned official reports (from the French Food Safety Agency, the High Council on Public Health or from PHF), making it difficult to understand. In 2016, the French Food Safety Agency released a literature review report updating previous international reviews and official reports on the relationships between food, diet and health (ANSES 2016b). According to this report, dairy consumption is associated with a probable reduction of the risk of type 2 diabetes, and milk consumption is associated with a probable reduction in colorectal cancer risk (ANSES 2016b). In a more recent report, the World Cancer Research Fund (WCRF) confirmed the probable protective effect of milk on colorectal cancer by extending it to all dairy products (WCRF/AICR 2017). In addition, the literature review report of the French Food Safety Agency (ANSES 2016b) indicated that while limited data suggest that consumption of dairy products is associated with increased risk of prostate cancer, other data suggest a reduced risk of cardiovascular disease (the second cause of death in France for both genders, after all cancers). More recently, a large international prospective study, the *PURE* study, reported a lower total cardiovascular mortality and total mortality risk with dairy consumption higher than 2 portions/day (median equal to 2.9 portions/day) (Dehghan *et al.* 2018). Finally, it is noticeable that dairy products are part of the French food culture and they are relatively inexpensive sources of essential nutrients (Maillot *et al.* 2007), two fundamental dimensions to be considered when establishing national food guides (Joint FAO/WHO Consultation 1998).

This study is subject to limitations. Like all studies based on dietary surveys, the results are subject to various biases (*e.g.* reporting bias) and depend on the quality of data used. For instance, in this study we used dietary data (food intakes and nutrient content of food items) that were 13-14 years old. Nevertheless, these limitations have less impact in this study since the objective was not to analyse the observed diets *per se* but to compare them to the modelled diets. Another limitation is that modelling the diets to be isocaloric with the observed diets is not necessarily suitable for individuals who may need to reduce their energy intake while adopting better food choices. However, in the absence of accurate data on individual energy needs in the French *INCA2* survey, the assumption of stable energy intakes seemed to be the most reasonable methodological choice. In addition, given the theoretical nature of the modelling approach used and the absence of biological data associated with the food survey, it is not possible to predict the health impacts of a deterioration (or of a failure to improve) of the prevalence of inadequate intakes identified for certain nutrients. It should also be noted that the results of the modelling process directly depend on the constraints entered in the model, which themselves are an interpretation of the dietary guidelines tested. To be included in an optimisation model, the constraints must necessarily be quantified, which was not the case of all dietary guidelines. Some interpretation was therefore needed. Regarding meat, a larger imposed reduction might have been expected in the modelled diets, but the 2017 guideline was to 'limit the consumption of red meat and favour the consumption of poultry' (HCSP 2017), which is clearly not an explicit recommendation to reduce total meats. However, the newest and simplified version of the French FBDGs has been launched recently for communication to the public (Santé Publique France 2020): it does now use the word 'reduce' for red meat (but not for total meat). Regarding sweet products and free sugars, they were not (or were only slightly) reduced in modelled diets, which may raise questions about our interpretation of the corresponding guidelines. However, in the original guidelines published in the 2017 report of the High Council for Public Health (HCSP 2017) which were modelled in this study, the terms 'limit' or 'no more than' – but not 'reduce'– were used for sweet products and drinks, so that imposing a reduction on everyone would not necessarily have been in line with the guidelines as they were formulated at that time. Interestingly, the updated and simplified version of the French FBDGs for public communication now explicitly uses the word 'reduce' for sweet products and drinks (Santé Publique France 2020).

A stricter interpretation of the 'limit' guidelines for sweet products and drinks, and for added fats, as well as for meat and deli meats (*e.g.* imposing a systematic reduction, even when the maximum limits were not exceeded) could have been made, and other results would have been obtained. However, it is not clear that being more severe regarding limitation of sweets and meat would have improved the situation for the nutrients identified as problem nutrients in this study, namely fibre, calcium, iodine, EPA + DHA and vitamin D. It may have improved the level of fibre but probably not sufficiently to reach the AI of 30 g/day, already identified as almost impossible to reach in the population diet optimisation study conducted by the French Food Safety Agency (ANSES 2016d). Allowing fish more than twice a week would have improved the situation for EPA + DHA and vitamin D, but it would have clearly contradicted the recommendation. Also, the new French FBDGs recommend consuming organic food 'when possible' and favouring variety to reduce contaminant intakes, but this could not be taken into account into the models presently used. The newest version of French FBDGs for communication to the public is now recommending to limit 'ultra-processed' foods (Santé Publique France 2020), but this guideline was not included in the original 2017 report of the High Council for Public Health modelled in this study (HCSP 2017).

Finally, since it is not easy to predict what would be preferable: higher MAR but MER less reduced (*i.e.* DP3 model), or MAR not so high but MER much reduced (*i.e.* DP2 model), the present results may suggest that a recommendation of consuming 2 to 3 portions of dairy products per day would help to keep the best of each model and would be, therefore, an interesting alternative to the current recommendation of 2 portions per day.

Conclusions

Mathematical optimisation of individual diets is a powerful tool to test existing FBDGs and potential alternatives. Applied to the French case, the results suggest that complying with current FBDGs, as interpreted in the models tested, would improve the overall nutritional quality of the diet of adults in France. However, the risk of inadequate calcium intakes would be increased without enabling the recommendations on iodine, fibre and long-chain omega-3 fatty acids to be fully met.

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Conflicts of interest

MS-Nutrition and INRA obtained a financial contribution from the CNIEL to conduct this study. M.M. is employee of MS-Nutrition. N.D. is employee of the INRA. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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