Simulations of diet recommendations and assessment of their economic, environmental and nutritional impacts.

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Abstract: We analyse ex-ante the sustainability effects of diet recommendations in France, Denmark and Finland to conclude that: 1- The promotion of several diet recommendations would improve social welfare; 2- Healthy-eating recommendations targeting consumption of fruits/vegetables, salt and saturated fat should be prioritized for promotion; 3- Although synergies dominate, trade-offs between environmental and health objectives occur in some cases ; and 4- The taste/utility cost of dietary change imposed on consumers should be included in the welfare analysis of diet recommendations.

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ABSTRACT

We analyse ex-ante the effects of diet recommendations in France, Denmark and Finland. The simulation approach combines a behavioural model of adjustment to dietary constraints, an epidemiological model and a life-cycle analysis model. We conclude that for the three countries: 1- The promotion of several diet recommendations would improve social welfare; 2- Healthy-eating recommendations targeting consumption of salt, saturated fat and fruits/vegetables should be prioritized for promotion; 3- Although synergies dominate, trade-offs between environmental and health objectives may occur in some cases ; and 4- The taste/utility cost of dietary change imposed on consumers should be included in the welfare analysis of diet recommendations.

INTRODUCTION

The negative health and environmental effects of current diets in high-income countries is an issue that has moved up the policy agenda in recent years. The standard policy response has been to develop informational measures to urge consumers to modify their food choices towards healthier options, but the effects of such measures are poorly understood. Although a few rigorous ex-post economic analyses of such measures have been developed (Capacci and Mazzocchi, 2011; Shankar et al., 2013), ex-ante analyses of their potential economic, health, environmental and welfare effects are practically missing, with the few exceptions upon which this paper is based (and to which we return below). Comparatively, the sustainability impacts of differentiated food taxes and subsidies have been investigated more thoroughly, even though policy makers are typically reluctant to introduce that type of coercive measure.

This lack of understanding of the effects of diet recommendations raises a number of difficulties in the design and implementation of public policies aimed at promoting healthy eating and sustainable food consumption. For instance, given that consumers do not respond to complex messages, the first step in designing an informational campaign is to select a clear target, that is, a food or nutrient whose consumption should be encouraged or discouraged. However, the existing toolkit of researchers cannot produce a clear ranking of diet recommendations based on commonly accepted criteria (e.g., relative cost-effectiveness). The practical implication of this state of affair is that, for a given country at a given time, there is no rigorous way of establishing whether, say, promotion of fruits and vegetable consumption should be prioritised over measures targeting the consumption of meat or intake of salt.

The overall social desirability of such dietary recommendations and their promotion also remains an open question, which means that it is unknown whether more or less public resources should be allocated to support that type of policy. Indeed, many authors question the effectiveness of informational measures to change diets, pointing to seemingly limited effects on behaviours (Traill, 2012), although complete welfare analyses are almost non-existent.

A last shortcoming of the available literature is that it does not provide a metrics to measure the difficulty of complying with different recommendations for selected groups of the population. This is unsatisfactory because research has shown that the adoption of dietary recommendations and related dietary change by consumers are often difficult for many, as informational campaigns often raise awareness without having a large impact on behaviours (Pérez-Cueto et al., 2013). One potential explanations lies with the "taste cost" of dietary adjustments, that is, the loss of utility/hedonic rewards (e.g., taste, convenience) induced by a dietary change that brings a new balance between long-term health goals and short-term pleasure. In other words, the difficulties in complying with nutrient and food-based guidelines are likely due to the lack of compatibility of consumers' preferences with the diets that they would have to adopt in order to comply with these guidelines, but that issue has not been analysed on the basis of a clear conceptual framework.

Against this background, this report presents a model of consumer response to dietary recommendations that has previously been proposed by some of its authors to investigate the health and economic effects of dietary recommendations in France (see Irz et al., 2015). That model was subsequently extended to cover environmental effects (Irz et al, 2016a) and uncertainty in health outcomes (Irz et al., 2016b)[1], also in a French context. In light of that work, the main contribution of this report is to apply the same model to different European countries, namely Denmark and Finland, in pursuit of several objectives: 1- To establish whether that approach is robust; 2- To assess whether the main results found in France – for instance regarding the relative magnitude of health and environmental benefits of various recommendations, or the synergies between environmental and health goals - also apply in different national contexts and hence may have general validity; and 3- To deliver practical advice regarding the promotion of sustainable diets in the three countries.

The report is organised as follows. The next section gives an overview of the methodology, presenting the theoretical model and the procedure used to calibrate it to the three countries. Presentation of the most salient results follows, and the report ends by offering some general conclusions.

[1] That paper is an output of SUSFANS and therefore presented in an appendix at the end of this document.

METHODS

The theoretical model

Overview - The schematic structure of the model is presented in Figure 1. At its core is a behavioural model using empirically estimated preferences to simulate how a representative consumer complying with one or several new dietary constraints would adjust his/her diet, as well as the short-term utility loss due to compliance, which we call the taste cost of the adjustment. Those adjustments are then linked to an epidemiological model to calculate health effects, and a life-cycle analysis (LCA) model to simulate environmental effects. Monetization of the health and environmental effects allows calculation of the benefit from compliance, which can be compared to the private taste cost and public policy costs in an integrated efficiency analysis. The simulations can be carried out for any number of sub-populations for which data and parameters are available, hence allowing for the analysis of the equity effects of recommendation (e.g., is compliance more difficult for low-income groups? Which groups derive the largest health benefit from compliance? etc.). We now turn to each sub-components of the model. Although this model starts from an "as if" assumption in the sense that it assumes compliance with a given recommendation (or set of recommendations), the analysis delivers useful information to compare the sustainability effects of recommendations and their impacts on welfare.

The behavioural model – The starting point is a model of whole diet adjustment to nutritional and/or environmental constraints (i.e., "dietary constraints") presented in more details in Irz et al. (2015) and based on the generalised rationing theory of Jackson (1991). We assume that an individual chooses the consumption of H goods in quantities $\boldsymbol{x}=(x_1,\ldots x_H)$ to maximize a strictly increasing, strictly quasi-concave, twice differentiable utility function $U(x_1,\ldots x_H)$, subject to a linear budget constraint $\boldsymbol{p}.\boldsymbol{x} \leq M$, where $\boldsymbol{p}$ is a price vector and M denotes income. We further assume that the consumer operates under N additional linear dietary constraints, imposing, for instance, a maximum permissible consumption of salt, or total greenhouse gas (GHG) emissions from the diet, or a minimum consumption of fruits and vegetables (F&V). Denoting by a_n^i the constant nutritional or environmental coefficient (henceforth referred to as technical coefficient) for any food i and target n, the value of which is known from life cycle analysis (LCA) or food composition tables, the dietary constraints are expressed as:

$$\sum_{i=1}^{H} a_i^n x_i \leq r_n \;\forall n = 1,\ldots, N \qquad (1)$$

The utility maximization problem is solved first in a Hicksian framework (i.e., holding utility constant). We denote the compensated (Hicksian) demand functions of the non-constrained problem by $h_i(p,U)$, and those of the constrained model by $\tilde{h}_i(p,U,A,r)$, where A is the *(N* x *H)* matrix of technical coefficients, and r the *N*-vector of levels of the constraints. The solution requires the derivation of shadow prices $\tilde{p}$, defined as the prices that would have to prevail for the unconstrained individual to choose the same bundle of goods as the constrained individual: $\tilde{h}_i(p,U,A,r) = h(\tilde{p},U)$. In the simplified situation where only one dietary constraint is imposed (i.e, *N*=1), the marginal change in shadow prices derived in Irz et al. (2015) are:

$$\frac{\partial \tilde{p}_i}{\partial r_1} = a_i^1 / (\sum_{i=1}^{H}\sum_{j=1}^{H} s_{ij} a_i^1 a_j^1) \qquad i = 1,....H \qquad (2)$$

where $s_{ij} = \partial h_i / \partial p_j$ denotes the Slutsky coefficient of good *i* relative to price *j*. The corresponding adjustments in Hicksian demand induced by compliance with the constraint follow:

$$\frac{\partial \tilde{h}_k}{\partial r_1} = (\sum_{i=1}^{H} s_{ki} a_i^1) / (\sum_{i=1}^{H}\sum_{j=1}^{H} s_{ij} a_i^1 a_j^1) \qquad k = 1,....H \qquad (3)$$

Equation (3) expresses the changes in compensated demands as functions of two sets of parameters only: first, the Slutsky coefficients, which describe consumers' preferences and the relative difficulty of substituting foods for one another; and, second, matrix *A*, which gathers technical coefficients measuring the properties of each food in the nutritional and environmental domains. Given that the Slutsky matrix is typically estimated empirically from observations on actual purchase behaviours, we claim that the model is based on realistic food preferences, unlike virtually all programming-based models of diet optimization that make arbitrary assumptions about food preferences, either explicitly (i.e., by imposing "palatability constraints", as for instance in Henson, 1991) or implicitly (through the choice of an arbitrary objective function, as in Shankar et al., 2008 or Darmon et al., 2008).

Expressions (3) and (4) show that a change in the nutritional constraints has an impact on the entire diet. This is true even for the goods that do not enter the constraints directly, as long as they entertain some relationship of substitutability or complementarity with any of the goods entering the constraints (i.e., as long as at least one Slutsky term s_{ki} is different from zero). Further, the model indicates that the magnitude and sign of any change in demand for any given product is unknown *a-priori* but depends in a complex way on the product's technical coefficients and its substitutability with other products entering the constraints.

The extension of the model to the case of *N<H* environmental constraints is explained in detail in the annex of Irz et al. (2015), so that we only present the main results here. Expressing the solution of the expenditure minimization problem with multiple constraints requires the introduction of vectorial and matrix notations. We partition the *N*x*H* matrix of technical coefficients *A* as follows:

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1N} & \cdots & a_{1H} \\ a_{21} & & & & & \\ \vdots & & & & & \\ a_{N_1} & & & & & a_{NH} \end{pmatrix} = (BC)$$

$$where$$

$$B = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & & & \\ \vdots & & & \\ a_{N1} & & & \end{pmatrix} \text{ and } C = \begin{pmatrix} a_{1N+1} & a_{1N+2} & \cdots & a_{1H} \\ a_{2N+1} & & & \\ \vdots & & & \\ a_{NN+1} & & & a_{NH} \end{pmatrix}$$

Denoting by S the Slutsky matrix and I_N the identity matrix of dimension N, the change in the H-vector of shadow prices with respect to the N-vector defining the levels of the constraints is:

$$\frac{\partial \tilde{P}}{\partial r} = \begin{pmatrix} \left[A.S. \begin{pmatrix} I_N \\ C'.(B')^{-1} \end{pmatrix} \right]^{-1} \\ C'.(B')^{-1}. \left[A.S. \begin{pmatrix} I_N \\ C'.(B')^{-1} \end{pmatrix} \right]^{-1} \end{pmatrix} \tag{4}$$

The full matrix of elasticities of Hicksian demands with respect to the nutrient constraints follows:

$$\frac{\partial \tilde{h}}{\partial r} = \frac{\partial h}{\partial \tilde{P}} \frac{\partial \tilde{P}}{\partial r} = S. \begin{pmatrix} \left[A.S. \begin{pmatrix} I_N \\ C'.(B')^{-1} \end{pmatrix} \right]^{-1} \\ C'.(B')^{-1}. \left[A.S. \begin{pmatrix} I_N \\ C'(B')^{-1} \end{pmatrix} \right]^{-1} \end{pmatrix} \tag{5}$$

Equation (3) in the case of one constraint and equation (5) in the case of N constraints provide an empirical way of measuring the response of compensated (i.e., utility constrained) demands to the introduction of dietary constraints. However, real world consumers operate under a budget constraint rather than a utility constraint, and there is therefore a need to recover changes in uncompensated (i.e., budget constrained) demands. This is achieved by first calculating the compensating variation, which measures the loss of utility due to the imposition of the dietary constraints. For any change in the vector of constraint levels r, we have: $CV = -\sum_{i=1}^{H} p_i \partial \tilde{h}_i / \partial r_j < 0$. An approximate solution to the change in Marshallian demand Δx is then calculated by adding to Δh the income effect associated with the removal of the compensation: $\Delta x = \Delta h + \tilde{h}.\varepsilon^R CV / p.\tilde{h}$, where ε^R denotes the vector of income (or expenditure) elasticities, which is empirically estimable.

The epidemiological and environmental models - Simulation of health effects first requires that changes in food consumption at household level, as described by the behavioural model, be translated into changes in individual intakes. This is accomplished under the assumption that (i) the percentage changes in intakes are the same for all the members of a given household, and (ii) the percentage changes are the same for at-home and out-of-home consumption. Changes in food intakes are then converted into changes in nutrients using food composition tables. Variations in nutrient intakes are finally translated into changes in mortality due to diet-related chronic diseases using the DIETRON epidemiological model of Scarborough et al. (2012). Based on relative risk ratios derived from world-wide meta-analyses, the model converts variations in ten nutritional inputs (fruits, vegetables, fibres, total fat, mono-unsaturated fatty acids (MUFA), poly-unsaturated fatty acids (PUFA), saturated fatty acids (SFA), trans-fatty acids (TFA), cholesterol, salt, energy) to estimate changes in diet-related chronic diseases (heart disease, strokes, and ten types of cancer) and related deaths. The environmental effects are limited to an analysis of climate impact, which is estimated by applying LCA coefficients to each intake category.

Efficiency analysis – the behavioural model simply assumes compliance with dietary recommendations without considering the policy measures that would be necessary to implement to bring about compliance. Although that simplification precludes carrying out a full cost-benefit analysis, we nonetheless derive important insights regarding the relative efficiency of various recommendations through calculation of an efficiency threshold, defined as the maximum amount that could be invested by public authorities in order to ensure compliance with a given recommendation. Formally, promotion of a recommendation generates health benefits (denoted B_h) in the form of deaths avoided and reduced environmental externalities (denoted B_e), which can be calculated by valuing the health and environmental effects estimated by the model. In the short-run, there are however costs imposed on consumers (i.e., the taste cost as measured by $-CV$ and capturing a loss of hedonic rewards), as well as (unknown) costs to the public sector (i.e., cost of interventions such as social marketing campaigns, denoted C_p). The cost effectiveness threshold of each recommendation is hence calculated as $C_p=B_e+B_h+CV$, giving us a means of comparing the relative efficiency of all the selected recommendations.

Data and calibration

France – the model's calibration is explained in Irz et al. (2015) so that we only give a brief overview here. Food consumption data originates from a representative panel of French households (KANTAR Worldpanel), which was used previously to estimate a matrix of price and expenditure elasticities of demand for food by Allais et al. (2010). We have used those behavioural parameters and related product aggregation scheme as reported in the supplementary material of that article. The intake and food composition data comes from the French dietary intake survey INCA2, and are freely available from the open data platform of the French government (https://www.data.gouv.fr/fr/datasets/donnees-de-consommations-et-habitudesalimentaires-de-letude-inca-2-3/). The parameters of DIETRON are not country specific, so that adapting the DIETRON model to France only requires calibration of the initial mortality levels, by relevant causes. This is achieved by using the INSERM data on mortality in France attributable to major diet-related diseases.

Finland[2] – The consumption data originates from the year 2012 Household Budget Survey (HBS), which used diary records of all food purchases destined for at-home consumption in a nationally representative sample of Finnish consumers (n=3495). This data supported the estimation of an approximate Exact Affine Stone Index (EASI) demand system (Lewbel and Pendakur, 2009), which presents several advantages over more common functional forms (e.g., AIDS). The product aggregation scheme was defined so as to allow both a nutritional assessment and an assessment in terms of climate change impact, and is similar to that used in the Danish model so as to facilitate comparison. The intake and food composition data came from the Finnish dietary intake survey FINDIET 2012, while the mortality data necessary to calibrate DIETRON are publicly available from the website of the Finnish Statistical Institute.

Denmark - The consumption data originates from the National Dietary Survey 2011-2013 (Pedersen et al., 2015), which is a representative sample based on 3,307 individuals' 7-day records of their intakes. The dietary intake data were disaggregated into more detailed commodity groups by means of household budget survey from Statistics Denmark and household purchase data from GfK Consumerscan Scandinavia panel (http://www2.gfkonline.dk/). An Exact Affine Stone Index (EASI) demand system was estimated on the basis of monthly data from the GfK panel dataset for the years 2006-2014, in order to obtain estimates of conditional price and budget elasticities for the same 20 commodity categories as for France and Finland.

For all countries, the LCA coefficients derive from a systematic review of the grey and academic literature, as explained in detail in Pulkkinen and Hartikainen (2016). We also limit the study to individuals between the age of 25 and 74 and therefore focus on the effects of dietary changes on premature deaths (i.e., occurring before the age of 75).

Valuation of costs and benefits –The starting point of the valuation of the health benefit is the threshold value of a Quality Adjusted Life Year (QALY) that is applied in

[2] Finland was included in order to develop the protocol for analysing the Danish data.

the UK to investigate the cost-effectiveness of medical care (e.g., drugs, procedures). That threshold, discussed in McCabe et al. (2008) and still recommended by the UK National Institute for Clinical Excellence (NICE), lies within the £20-30k range, which translates roughly into €24-36k at the current exchange rate. Given that epidemiological data show that the average number of Life Years Saved (LYS) per DA is larger than 10 for most causes of mortality covered by DIETRON, we make the conservative assumption of 10 QALYs per DA, which implies a value of a DA in the €240-360k range. Leaning on the side of caution, we select the lowest value in this range, and the monetized health benefits should therefore be treated as lower bounds. In fact, that valuation of DA is much lower than the values of a statistical life (VSL) typically used in the cost-benefit analysis of public projects (e.g., road improvement), as reviewed by Treich (2015). On the environmental side, there is much debate regarding the social cost of greenhouse gas emissions (Stratham, 2013). To address this uncertainty, we rely on the meta-analysis of the social cost of carbon developed by Tol (2012). That author, after fitting a distribution of 232 published estimates, derived a median of €32/ton, a value which we adopt due to its rigour and objectivity.

Choice of constraints – We choose to analyse the sustainability effects of a number of dietary constraints, based on previously available results for France (i.e., constraints generating the largest benefits or level of efficiency) as well as issues currently hotly debated with regard to food consumption. Irz et al. (2016a) found that the recommendations most commonly promoted on health grounds and targeting consumption of salt, F&V and saturated fat ranked highest in terms of overall efficiency in France. Those three constraints are therefore included in the comparison. In addition, the debate over the climate impact of current diets in high-income countries has intensified, based on solid evidence that that effect is significant, typically ranging from 15% to 30% of total GHG emissions (Esnouf et al., 2013). Further, it has been shown consistently that per unit impacts vary enormously across foods, so that dietary adjustments with existing foods could generate large climate benefits. Thus, many authors have recommended a reduction in meat consumption (particularly meat from ruminants) and substitutions with plant-based foods (Stehfest et al., 2009; Berners-Lee et al., 2012). We therefore test the impact of two recommendations to reduce meat consumption, one for all meat, and the other one for red meat only. An alternative policy approach would rely on the development of carbon labels for foods, as piloted in many countries (Cohen and Vandenbergh, 2012) together with informational measures to persuade consumers to reduce their climate impact. With that in mind, a constraint on the total greenhouse gas emissions from foods, measured in terms of CO2 equivalent (CO2e) is also introduced in the analysis.

RESULTS

Table 1 describes the behavioural adjustments that take place when the six constraints are imposed on French, Finnish and Danish consumers, in each case considering a 5% variation from current levels (i.e., +5% in the case of F&V whose consumption should be encouraged, -5% for all other targets (foods/nutrients/CO2e) that should be reduced). For each country and each constraint, the table presents two columns: the left one reports the contribution of each food group to the constrained quantity (e.g., total consumption of F&V; CO2e), hence giving a depiction of current diets in relation to the targeted characteristic. Thus, in the case of France, the consumption aggregate “F&V” accounts for 93% of total F&V consumption, but the table also shows that 7% of F&V consumption originates from other consumption aggregates (e.g., ready meals). Meanwhile, for each constraint, the right column reports the change in consumption resulting from the imposition of the constraint. Thus, in the French case, requiring a 5% increase in consumption of F&V results in a slightly more than proportional increase (+5.5%) in consumption of the aggregate F&V because, at the same time, product categories containing some F&V decrease (e.g., ready meals -12%).

The simulations reported in Table 1 allow us to highlight several characteristics of the dietary adjustments that take place following the imposition of sustainability constraints. First, the imposition of dietary constraints results in relatively large variations in consumption across the entire diet. Hence, in the French case, the imposition of the F&V constraint induces rational consumers to reduce their consumption of dairy products by 4%, which is quantitatively large and could be related to the French habit of eating either a fruit or a yoghurt as a dessert (hence, the two product categories are substitutes). In many cases, however, the adjustments would have been difficult to anticipate a priori, as illustrated by the relatively large increases in consumption of plant-based fats, animal fats and cheese resulting from the imposition of the “all meat” constraint in the Finnish model, or the large responses of demands for sugar-rich products and root vegetables to the imposition of the salt constraint in the Danish model. Further, one notices that within food groups, different product categories respond very differently to the imposition of a given constraint, so that substitutions occur both across large food groups and within those. For instance, the French results indicate that for four of the six simulated constraints, consumption of red meat and other fresh meat adjust in opposite directions. Similarly, in relation to the Finnish results, imposition of a reduction in CO2e from the diet results in a decrease in consumption of beef/lamb and poultry, but also a less expected increase in consumption of pork and processed meat. The signs of the demand responses within broad category aggregates appear more homogenous in the Danish simulations.

Altogether, the simulations depict complex behavioural responses involving large substitutions among product groups, implying that simulating compliance with a given recommendation (e.g., F&V +5% or 5 portions) under a ceteris paribus assumption (i.e., holding constant all other components of the diet) would be inappropriate. The results also cast doubts over the ability of researchers to develop “reasonable” substitutions ex-ante or to impose ad-hoc palatability constraints in diet modelling.

Table 1 further reveals that the patterns of adjustment are specific to each country both qualitatively and quantitatively, although we find some similarities for some constraints. The first point is best illustrated with reference to the adjustments to the imposition of the salt constraint, which differ greatly across the three countries – for instance, compliance with that constraint induces consumption of meat and dairy to rise in France but shrink in Finland, while in Denmark the model predicts an increase in dairy consumption coupled with a decrease in meat consumption. Still with regard to the imposition of the salt constraint, the positive variation in consumption of F&V is quantitatively much larger in Finland (12%) than in France (3%) or Denmark (2%).

A few regularities also emerge from Table 1. Hence, in all three countries, raising exogenously consumption of F&V induces a reduction in meat consumption and, symmetrically, imposing an exogenous decrease in meat consumption results in a rise in consumption of F&V, thus indicating strong substitutions between the two food categories. However, the simulations reveal, overall, country-specific patterns of adjustments to the imposition of dietary constraints. This level of heterogeneity in response is, of course, not unexpected as it is known that current diets vary across EU countries (Slimani et al., 2002) and that there are strong cultural influences on food preferences (Tiu Wright et al., 2001).

Table 2 presents the economic, health and climate effects resulting from the imposition of the constraints. The taste cost measuring the short-term loss in hedonic rewards represents in each case less than 1% of the food budget and thus appears relatively small (although it is worth keeping in mind that we only test small/marginal changes in the constraint levels) . More informative, the ranking of those taste costs captures the relative difficulty of adjusting diets to comply with recommendations and, in that respect, Table 2 indicates that consumers vary across countries, and that differences are more pronounced between France and the two Nordic countries. According to the simulations, imposition of the F&V constraint in France would impose much larger taste costs on consumers than in Finland and Denmark, where consumers appear to face greater difficulties to modify their diets in order to reduce intake of salt. In all three countries, we also note that the taste cost of reducing consumption of all meats is significantly larger than the taste cost of only reducing consumption of red meat, which illustrates the fact that cross-category substitutions are more difficult for consumers to achieve than within-category substitutions (i.e., among relatively close substitutes). Another general result is that the direct targeting of CO2 emissions is associated with relatively large taste costs, so that it may be more efficient to seek reductions in GHG emissions indirectly by formulating recommendations about other aspects of the diet.

Through the quantification and ranking of taste costs, the model also delivers some practical insights, for instance that it is much easier to encourage F&V consumption in Finland and Denmark than in France, while reducing consumption of salt through dietary change may be more challenging in Finland and Denmark than in France.

Further, although the taste costs are small relative to the food budget, they still account for millions of euros when expressed annually for whole populations. Those costs are typically ignored when assessing the social desirability of measures aimed at promoting healthy eating (e.g., Rajgopal et al., 2002).

The health effects are calculated as the annual number of deaths avoided due to the dietary changes induced by each constraint and vary from a few hundreds to almost 3000 for France and from none to over 500 for Finland and Denmark. Those health effects are deemed quantitatively significant as they account for up to 7% of the diet-related deaths captured by the epidemiological model DIETRON in the case of Finland, 4% in the case of France and 3% in the case of Denmark (keeping in mind the relatively small 5% exogenous change in constraint levels). We also observe some consistency among the three countries in the relative magnitudes of the health effects: in all cases, a reduction in consumption of all meat and red meat delivers little health benefit, while the salt and SFA constraints generate relatively large health improvements. The health effects of raising F&V consumption are substantial in all three countries but also, in relative terms, much larger in France than in Finland and Denmark. Finally, reducing the GHG impact of the diet results in substantial health gains in France and Finland but not Denmark.

An important insight of the simulations is that whole-diet adjustments and substitutions may sometimes cause unintended and undesirable health effects. Hence, while the three traditional public health measures of reducing consumption of salt and SFA and increasing consumption of F&V are unambiguously associated with health improvements, the health effects of more environmentally motivated measures, such as reductions in meat consumption or GHG from the diet, may be negative. This is most visible in the Danish case, with simulations suggesting negative health gains from imposition of the all meat, red meat and GHG constraints.

Table 2 further indicates that the pathways to better health differ in the three countries, with cardio-ischemic diseases accounting for a larger share of DA in Finland and Denmark than in France, which we explain by the relatively larger incidence of those diseases in Nordic countries than in France. For that country, reductions in mortality from diet-related cancers account for about 50% of the total number of deaths avoided, although this varies across constraints.

The climate impact of the dietary adjustments simulated by the model is presented in the lower part of each country section in Table 2. As expected, the three constraints introduced primarily with the objective of reducing that impact generate lower emissions of greenhouse gas emissions in the three countries, but the reductions are relatively small for the two meat constraints, especially in the case of Finland (i.e., less than 1%). The environmental effects driven by the imposition of the other constraints with primarily public health objectives vary among the three countries. In particular, for France, the results suggest that there are always synergies between health and environmental objectives, with adoption of healthier diets in terms of F&V, salt and FSA also delivering reductions in GHG emissions. In the case of Finland, there are trade-offs between health and environmental objectives, since reductions in consumption of SFA and salt, which are desirable from a health point of view, unfortunately generate higher levels of diet-related GHG emissions. This is explained by the complex substitutions reported in Table 1: the decrease in salt intake leads Finnish consumers to reduce their consumption of processed meat but increase that of red meat and cheese. Similarly, a decrease in SFA intake leads to an increase in consumption of red meat and processed meat. In the case of Denmark, it is worth noting that the simulated environmental effect of imposing a reduction in SFA is also negative (although small).

Thus, altogether, Table 2 brings to light that while healthier diets also tend to be more climate friendly, the possibility of trade-offs in sustainability dimensions is very present when considering real-world consumers and their preferences.

Table 3 pieces together the economic, health and environmental effects to calculate the efficiency thresholds for the two countries and six constraints. As explained in the methodology section, that threshold represents the maximum amount that could be used by public authorities to promote a recommendation while ensuring that total benefits exceed total costs, assuming that the 5% target for the constrained quantity is attained. In the case of France, the efficiency thresholds C_p are positive and large for all six constraints, but reductions in consumption of salt and SFA, as well as an increase in consumption of F&V, should be prioritised over reductions in meat consumption and measures aimed at reducing the carbon impact of diets. We note, however, that the thresholds are in all cases large, amounting to up to half a billion euros for the salt constraint, and still worth €30 million annually for the “all meat” constraint. Those sums typically exceed the cost of public information campaigns aimed at inducing consumers to change their diets. For instance, Capacci and Mazzocchi (2011) report that the ambitious “5-a-day” UK campaign to encourage consumption of F&V, which was partially successful since it raised consumption by 8%, had a total budget of less than £3 million (roughly €4 million). On that basis, our results support the idea that more resources should be allocated to the promotion of sustainable diets in France through provision of information.

In the case of the two Nordic countries, the estimated efficiency thresholds are smaller than those calculated for France, and they also vary in signs across constraints. The smaller thresholds reflect in part the smaller populations of those two countries, but those are netted out in the figures presented in parentheses in the table.[3] More importantly, the results show that for both Finland and Denmark, some thresholds are also very high, with (unscaled) maxima worth €53 million and €126 million

[3] In other words, the Danish and Finnish thresholds are scaled up by factors equal to 11.75 and 12.21 respectively, which are ratios of the French population to the populations of those two countries.

respectively. Thus, the cross-country comparison reinforces the conclusion that promotion of some dietary recommendations is likely to be socially desirable.

The second similarity in results across countries relates to the ranking of the recommendations based on the values of the efficiency thresholds. For all three countries, we find that the three constraints traditionally promoted on public health grounds and targeting consumption of F&V, salt and SFA rank highest, while the three environmentally-motivated constraints rank lowest. We therefore conclude that, at least on the basis of that aggregate criterion, there does not appear to be an obvious need to modify dietary recommendations in those three countries to take account of climate impact. We note, however, that that conclusion only holds if one accepts the commensurability of benefits in the health and environmental domains, since the Danish and Finnish simulations also show that promotion of several public health measures may generate increases in GHGE emissions (Table 2). Thus, the results must be interpreted while keeping in mind that there remains much debate about the appropriateness of adding health and environmental benefits (Munda, 2016). The only measure that appears cost effective in all three countries and would generate positive effects on both health and the environment is the promotion of F&V consumption.

Among the most cost-efficient recommendations, there are also relevant cross-country differences, and we note in particular that the SFA constraint ranks top in both Denmark and Finland, but not France. This can be explained in part by differences in disease burdens and related health effects since, as previously mentioned, cardio-vascular diseases are relatively more prevalent in Nordic countries than in France, where, in turn, cancers are responsible for a larger share of the diet-related disease burden.

Compared to the previously published results for France, our cross-country analysis also suggests that the direct targeting of meat consumption and GHG emissions may not always be efficient, since five of the six corresponding efficiency thresholds calculated for Denmark and Finland are actually negative, while the only positive one is also small. In the case of Denmark, a sensitivity analysis (not reported) further shows that those results are robust to the choice of parameters used to value DA and GHG emissions, as they are explained primarily by the negative health effects of those recommendations. In the case of Finland, a similar sensitivity analysis establishes that the efficiency threshold for the CO2 constraint responds strongly to the valuation parameters and that, with larger but still reasonable parameters to value either GHG or DA, promotion of that constraint appears cost effective. Thus, for that recommendation and country, the magnitude of the estimated taste costs plays a crucial role in determining whether the measure is cost-effective, although, as mentioned in the introduction, those taste costs are typically ignored in the analysis of dietary recommendations.

Finally, Table 3 indicates that, for all three countries, the largest share of the benefit from compliance with the constraints originates from improvements in health rather than a reduction in climate impact. As expected, the relative importance of the environmental benefit is larger for the two meat constraints and the CO2 constraint than for the three public health constraints.

CONCLUSIONS

This paper applied a novel approach to the ex-ante analysis of the sustainability effects of diet recommendations in French, Danish and Finnish contexts. The cross-country comparison of results demonstrates that consumers in different countries adjust differently to similar recommendations. This was largely expected from the theory, which implies that changes in consumption and related effects depend on several factors, including the initial diet, food preferences as measured by elasticities, the nutritional composition of foods, as well as the initial burden of diet-related chronic diseases.

The simulations also indicate that there exist clear synergies in the pursuit of healthy and climate friendly diets in France, but that in Finnish and Danish contexts trade-offs may exist, with some healthy-eating recommendations resulting in larger greenhouse gas emissions and some environmental constraints inducing health losses. Those trade-offs are explained by whole diet substitutions driven by consumers' preferences. Thus, the analysis points to the need to carefully tailor the design of diet recommendations to each country's context, and the necessity to factor in the food preferences of consumers in the analysis of those recommendations.

However, for all countries, we reach the same overarching conclusions that: 1- The promotion of some diet recommendations is clearly welfare improving, so that it would be desirable to allocate more resources to it; 2- The recommendations with the traditional public health goals of reducing consumption of salt and SFA, and encouraging consumption of F&V, should be prioritized for promotion if one accepts the commensurability of environmental and health benefits. In that case, this also means that there is no obvious need to reformulate current recommendations to take account of the climate effect of diets; 3- Although synergies dominate, trade-offs between climate and health objectives may occur for some recommendations and some recommendations; and 4- Taking account of the taste/utility cost of dietary change imposed on consumers is important in the welfare analysis of diet recommendations, although that cost has been ignored in most of the existing literature on the subject.

In further analysis, we will test the robustness of those conclusions by extending the sensitivity analysis with respect to other key parameters of the model (e.g., relative risk ratios of the epidemiological model, elasticities).

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TABLES AND FIGURES

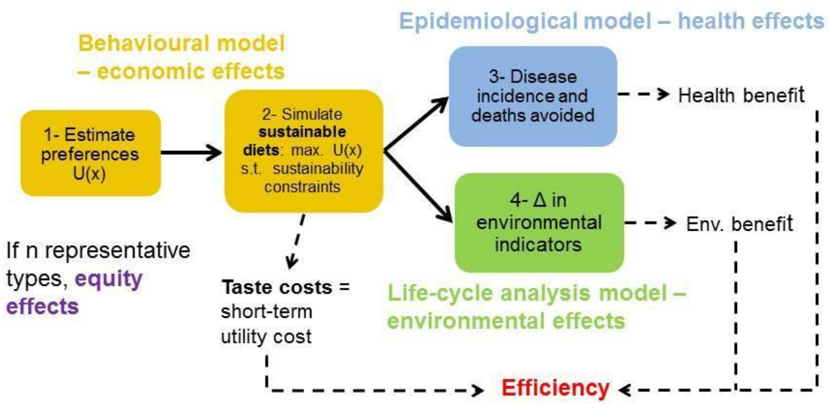

Figure 1 – Overall structure of the model

	France (lower-average income quartile)											
	Constraints											
	F&V +5%		Salt -5%		SFA -5%		All meat -5%		Red meat -5%		CO2e -5%	
All meat	**0.0**	**-0.3**	**23.4**	**1.7**	**16.6**	**5.2**	**93.7**	**-5.2**	**89.7**	**-0.7**	**46.9**	**-3.0**
Red meat	0.0	-9.1	1.4	1.9	3.4	-0.3	22.7	-8.2	89.7	-5.5	28.0	-19.9
Other meats	0.0	6.2	2.7	4.6	4.4	14.1	38.8	-6.4	0.0	0.7	12.1	0.4
Cooked meats	0.0	-3.3	19.3	-2.5	8.8	-3.7	32.2	-1.3	0.0	0.8	6.8	4.1
Dairy	**0.0**	**-4.0**	**21.5**	**1.6**	**52.1**	**-5.9**	**0.0**	**3.4**	**0.0**	**0.6**	**23.3**	**0.2**
Milk products	0.0	-4.3	6.6	3.0	8.3	-5.5	0.0	3.3	0.0	0.7	11.7	0.0
Cheese/butter	0.0	-2.9	14.9	-4.0	43.8	-7.4	0.0	4.2	0.0	0.1	11.7	0.9
Other animal prod.	**0.0**	**3.2**	**5.1**	**6.6**	**2.7**	**-0.5**	**0.0**	**3.5**	**0.0**	**0.7**	**3.0**	**3.6**
Fish	0.0	9.7	3.7	7.6	0.7	8.7	0.0	7.5	0.0	1.7	2.0	8.9
Eggs	0.0	-7.6	1.4	4.9	2.0	-16.0	0.0	-3.3	0.0	-0.8	1.0	-5.4
Starchy foods	**0.2**	**-16.1**	**14.5**	**-10.2**	**2.2**	**0.1**	**0.0**	**-2.2**	**0.0**	**-0.9**	**2.2**	**-3.6**
Grains	0.2	-6.2	13.4	-16.5	0.7	-2.2	0.0	-0.3	0.0	-1.0	1.5	-3.4
Potatoes	0.0	-27.6	1.1	-2.8	1.5	2.8	0.0	-4.5	0.0	-0.8	0.7	-3.7
F&V	**92.7**	**5.5**	**8.3**	**2.6**	**0.9**	**3.9**	**0.0**	**0.6**	**0.0**	**0.6**	**6.9**	**2.4**
F - Fresh	40.7	-1.1	0.1	0.0	0.1	-5.0	0.0	2.7	0.0	1.5	1.8	5.9
F - Processed	2.8	27.0	0.0	2.2	0.0	-31.0	0.0	-3.2	0.0	0.2	0.3	-0.3
F&V juices	6.3	4.0	0.1	3.8	0.1	4.6	0.0	-0.3	0.0	0.8	1.4	2.6
V - Fresh	32.6	9.5	3.2	6.7	0.4	15.8	0.0	-0.3	0.0	-0.5	2.0	-1.0
V - Processed	9.9	18.4	4.8	-2.9	0.2	10.8	0.0	-2.7	0.0	0.0	1.3	-0.8
F - Dry	0.5	-6.0	0.1	12.0	0.2	-5.1	0.0	11.7	0.0	1.4	0.1	7.6
Other												
Ready meals	4.2	-11.7	9.2	-7.5	3.6	-5.7	6.3	-3.6	10.1	-1.1	5.5	-4.3
Oil, margarine	0.0	12.0	4.2	5.3	8.8	-2.6	0.0	-1.2	0.0	0.1	1.8	-0.7
Salt-fat prod.	0.0	-20.7	7.1	-27.6	1.0	-28.4	0.1	10.3	0.1	1.2	0.4	6.4
Sugar-fat prod.	2.9	2.1	5.6	-0.7	12.1	-5.9	0.0	0.3	0.0	0.1	4.4	0.5
Soft drinks	0.0	-18.4	0.2	-5.9	0.1	2.8	0.0	5.3	0.0	0.7	0.5	7.5
Water	0.0	-20.0	0.7	1.6	0.0	9.7	0.0	10.0	0.0	1.8	1.4	8.3
Alcohol	0.0	12.9	0.2	1.3	0.0	4.8	0.0	-0.4	0.0	0.3	3.6	1.0

	Finland (whole population)												Denmark (whole population)											
	Constraints												Constraints											
	F&V +5%		Salt -5%		SFA -5%		All meat -5%		Red meat -5%		CO2e -5%		F&V +5%		Salt -5%		SFA -5%		All meat -5%		Red meat -5%		CO2e -5%	
All meat	**0.0**	**-1.1**	**23.4**	**-4.1**	**11.7**	**3.7**	**94.3**	**-4.9**	**76.1**	**-0.9**	**30.4**	**-5.7**	**0.0**	**-1.3**	**43.3**	**-3.9**	**26.0**	**0.3**	**100.0**	**-4.9**	**100.0**	**-0.5**	**52.3**	**-0.5**
Beef/lamb	0.0	-2.4	0.9	6.9	0.4	3.1	4.9	-4.0	51.2	-8.5	6.2	-31.8	0.0	-2.0	6.4	0.6	4.4	3.2	21.9	-5.6	87.4	-5.9	33.0	-5.9
Pork	0.0	-1.4	3.3	0.9	2.4	6.6	21.5	-6.2	0.0	1.2	5.7	5.1	0.0	-2.1	4.6	-4.3	1.9	1.1	18.2	-10.2	0.0	-0.8	5.5	-0.8
Poultry/other	0.0	-1.0	8.3	-1.0	3.7	-0.1	37.8	-2.8	0.0	-0.7	13.0	-11.1	0.0	-0.8	7.1	-3.8	0.8	1.6	19.6	-2.9	0.0	1.4	3.8	1.4
Processed	0.0	-0.9	10.9	-14.9	5.3	8.6	30.0	-7.7	24.9	-1.6	5.5	0.7	0.0	-0.9	25.2	-6.1	18.9	-2.6	40.2	-3.4	12.6	1.3	10.0	1.3
Dairy	**0.0**	**-1.2**	**17.7**	**-1.6**	**55.6**	**-0.1**	**0.0**	**1.2**	**0.0**	**0.4**	**30.5**	**-4.5**	**0.0**	**-0.8**	**10.6**	**1.0**	**47.4**	**-6.9**	**0.0**	**2.9**	**0.0**	**0.5**	**18.4**	**0.5**
Milk/other dairy	0.0	-1.0	5.9	-2.3	9.4	0.5	0.0	0.7	0.0	0.4	14.8	-5.7	0.0	-1.0	2.7	1.6	18.2	-7.5	0.0	3.0	0.0	0.5	8.2	0.5
Cheese	0.0	-3.1	5.7	6.2	9.7	0.1	0.0	3.0	0.0	0.5	8.2	-2.0	0.0	-0.7	6.5	-2.8	8.3	-1.0	0.0	2.1	0.0	0.4	6.5	0.4
Animal fats	0.0	-1.5	6.1	-3.1	36.5	-8.7	0.0	4.9	0.0	0.9	7.5	6.4	0.0	1.0	1.5	0.2	21.0	-11.0	0.0	2.6	0.0	0.5	3.7	0.5
Other animal prod.	**0.0**	**-0.54**	**3.3**	**5.3**	**1.0**	**1.6**	**0.0**	**0.5**	**0.0**	**-0.2**	**2.0**	**2.4**	**0.0**	**-1.5**	**4.6**	**2.1**	**0.2**	**4.1**	**0.0**	**0.2**	**0.0**	**-0.5**	**2.3**	**-0.5**
Fish	0.0	-0.5	3.3	5.3	1.0	1.6	0.0	0.5	0.0	-0.2	2.0	2.4	0.0	-1.5	4.6	2.1	0.2	4.1	0.0	0.2	0.0	-0.5	2.3	-0.5
Starchy foods	**6.5**	**-0.3**	**27.2**	**-4.2**	**9.6**	**-3.1**	**0.0**	**0.7**	**0.0**	**0.4**	**9.2**	**0.3**	**6.8**	**0.4**	**26.2**	**-6.2**	**7.5**	**-0.4**	**0.0**	**1.8**	**0.0**	**0.3**	**6.9**	**0.3**
Grains	1.4	0.3	24.2	-3.4	7.0	-3.1	0.0	1.8	0.0	0.9	7.3	4.6	1.3	-0.6	19.6	-2.3	7.4	-1.6	0.0	1.8	0.0	0.3	5.5	0.3
Roots, tubers etc.	5.1	-1.5	3.0	-6.2	2.6	-3.2	0.0	-1.8	0.0	-0.8	2.0	-9.3	5.5	2.3	6.7	-14.1	0.1	2.0	0.0	1.8	0.0	0.3	1.4	0.3
F&V	**89.1**	**5.7**	**3.2**	**11.6**	**0.5**	**3.1**	**0.0**	**0.9**	**0.0**	**0.4**	**8.6**	**7.2**	**92.3**	**5.2**	**7.8**	**2.3**	**3.1**	**1.6**	**0.0**	**1.9**	**0.0**	**0.3**	**7.7**	**0.3**
Fruits	55.1	6.0	0.4	12.8	0.2	2.8	0.0	0.7	0.0	0.4	4.9	7.1	52.7	6.2	0.1	3.9	3.0	0.9	0.0	1.9	0.0	0.3	3.8	0.3
Vegetables	34.0	5.2	2.8	9.5	0.4	3.5	0.0	1.2	0.0	0.2	3.7	7.4	39.6	4.0	7.7	0.5	0.1	2.5	0.0	1.9	0.0	0.3	3.9	0.3
Other																								
Composite dishes	2.4	0.5	3.6	5.1	1.9	-0.6	5.7	-1.5	23.9	-1.1	3.6	-7.4	0.0	-2.2	0.0	8.1	0.0	7.0	0.0	0.4	0.0	0.5	0.0	0.5
Plant based fats	0.0	-3.6	2.4	-35.1	7.9	-23.4	0.0	4.6	0.0	1.1	0.7	16.7	0.0	0.9	1.5	-0.9	9.5	-6.8	0.0	2.2	0.0	0.4	1.0	0.4
Snacks	0.0	-2.7	0.8	5.3	0.4	-8.4	0.0	-0.6	0.0	0.7	0.1	3.2	0.0	-1.1	0.8	4.8	1.8	-16.4	0.0	0.5	0.0	0.1	0.2	0.1
Sugar	0.0	-0.7	2.1	-2.1	8.5	-4.2	0.0	0.5	0.0	0.0	5.7	-0.9	0.0	-1.1	0.4	17.0	3.2	1.1	0.0	1.0	0.0	0.2	1.8	0.2
Soft drinks	0.0	-0.2	0.2	-3.9	0.0	-1.8	0.0	0.9	0.0	-0.8	0.6	0.5	0.0	-1.0	0.2	3.0	0.0	2.8	0.0	1.1	0.0	0.2	1.4	0.2
Tea/coffee/water	0.0	-1.6	0.3	18.8	0.2	4.3	0.0	1.5	0.0	-0.1	6.0	-6.9	0.0	-0.8	0.0	2.5	0.9	0.7	0.0	0.8	0.0	0.2	3.7	0.2
Residual category	2.0	-1.7	15.7	-14.7	2.7	0.2	0.0	0.5	0.0	-0.1	2.5	3.2	0.9	2.5	4.2	-41.8	0.3	8.1	0.0	1.1	0.0	0.2	0.5	0.2

Table 1: Impact of constraints on consumption

The table presents the contributions to the constrained quantity (for each constraint, shaded column, in %) and the adjustments in consumption (for each constraint, non-shaded column, in %).

	F&V +5%	Salt -5%	SFA -5%	All meat -5%	Red meat -5%	CO2e -5%
FRANCE						
Taste Cost						
Total (€M)	466	128	288	76	10	207
% food budget	**0.64**	**0.17 %**	**0.37 %**	**0.10 %**	**0.01 %**	**0.27 %**
DA for DIETRON diseases						
Total	2 506	2 844	2 138	245	229	1 140
% Dietron disease	**3.8 %**	**4.3%**	**3.2%**	**0.4%**	**0.3%**	**1.7%**
% CHD	34 %	28 %	36 %	21 %	28 %	44 %
% Stroke	17 %	19 %	26 %	22 %	19 %	12 %
% Cancers	49 %	53 %	38 %	57 %	53 %	44 %
CO2 equivalent						
Total (Kt)	-3167	-355	-47	-1487	-892	-4112
% change	**-4.5 %**	**-0.5 %**	**-0.1 %**	**-2.1 %**	**-1.3 %**	**-5.0 %**
FINLAND						
Taste Cost						
Total (€M)	4	78	18	9	-2	62
% food budget	**0.03 %**	**0.55 %**	**0.13 %**	**0.07 %**	**-0.01 %**	**0.43 %**
DA for DIETRON diseases						
Total	149	543	303	-4	10	123
% Dietron disease	**2.0 %**	**7.4 %**	**4.1 %**	**-0.1 %**	**0.1 %**	**1.7 %**
% CHD	54 %	58 %	59 %	41 %	66 %	45 %
% Stroke	16 %	19 %	22 %	75 %	13 %	19 %
% Cancers	30 %	24 %	19 %	-15 %	21 %	36 %
CO2 equivalent						
Total (Kt)	-16	167	36	-36	-44	-283
% change	**-0.3 %**	**2.9 %**	**0.6 %**	**-0.6 %**	**-0.8 %**	**-5.0 %**
DENMARK						
Taste Cost						
Total (€M)	8	61	12	16	6	36
% food budget	**0.05 %**	**0.42 %**	**0.08 %**	**0.11 %**	**0.04 %**	**0.24 %**
DA for DIETRON diseases						
Total	135	198	574	-54	-44	-69
% Dietron disease	**0.8 %**	**1.1 %**	**3.3 %**	**-0.3 %**	**-0.3 %**	**-0.4 %**
% CHD	47 %	42 %	58 %	24 %	48 %	42 %
% Stroke	8 %	29 %	19 %	53 %	31 %	41 %
% Cancers	45 %	30 %	23 %	23 %	22 %	17 %
CO2 equivalent						
Total (Kt)	-45	-22	18	-113	-97	-347
% change	**-0.6 %**	**-0.3 %**	**0.3 %**	**-1.6 %**	**-1.4 %**	**-5.0 %**

Table 2: Effect of recommendations on short-term consumer welfare, health and greenhouse gas emissions

	Benefits (M€)	% Health	Cost (M€)	C_p	Max Campaign	Ranking
FRANCE						
F&V +5%	703	86 %	466	237		2
Salt -5%	694	98 %	128	566		1
SFA -5%	515	100 %	288	226		3
All meat -5%	106	55 %	76	30		6
Red meat -5%	84	66 %	10	73		5
CO2e +5%	405	68 %	207	198		4
FINLAND						
F&V +5%	36	99 %	4	33	(398)	3
Salt -5%	125	104 %	78	47	(571)	2
SFA -5%	71	102 %	18	53	(652)	1
All meat -5%	0.1	-	9	-9	(-113)	5
Red meat -5%	4	63 %	-2*	4*	(47)	4
CO2e +5%	38	76 %	62	-23	(-285)	6
DENMARK						
F&V +5%	34	96 %	8	26	(302)	2
Salt -5%	48	99 %	61	-13	(-156)	3
SFA -5%	137	100 %	12	126	(1477)	1
All meat -5%	-9	-	16	-25	(-298)	5
Red meat -5%	-7	-	6	-14	(-163)	4
CO2e +5%	-5	-	36	-41	(-485)	6

* Theoretically inconsistent negative cost not included in calculation

Note: The Finnish and Danish figures in parentheses are scaled up by factors 12.21 and 11.75 respectively to account for differences in population size across countries. They are then comparable to the corresponding French figures.

Table 3: Efficiency analysis

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RESEARCH ARTICLE

Beyond Wishful Thinking: Integrating Consumer Preferences in the Assessment of Dietary Recommendations

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Abstract

Convenience, taste, and prices are the main determinants of food choices. Complying with dietary recommendations therefore imposes a "taste cost" on consumers, potentially hindering adoption of those recommendations. The study presents and applies a new methodology, based on economic theory, to quantify this taste cost and assess the health and welfare effects of different dietary recommendations. Then, by comparison of those effects, we identify socially desirable recommendations that are most compatible with consumer preferences (i.e., that best balance health benefits against"taste cost") and should be prioritized for promotion. The methodology proceeds in three-steps: first, an economic-behavioral model simulates how whole diets would change if consumers complied with dietary recommendations; second, an epidemiological model estimates the number of deaths avoided (DA) due to the dietary change; third, an efficiency analysis weighs the health benefits against the taste and policy costs of each recommendation. The empirical model is calibrated using French data. We find that recommendations to reduce consumption of red meat and soft-drinks, or raise consumption of milk products and fish/seafood impose relatively moderate taste costs. By comparison, recommendations related to F&V consumption and, to a lesser extent, butter/cream/cheese, snacks, and all meats impose larger taste costs on consumers. The F&V recommendation is the costliest for consumers to comply with, but it also reduces diet-related mortality the most, so that a large budget could be allocated to promoting F&V consumption while keeping this policy cost-beneficial. We conclude that promotion of most dietary recommendations improves social welfare. Our framework complements the programming models available in nutrition and public health: those models are best used to identify dietary targets, following which our framework identifies cost-beneficial ways of moving towards those targets.

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Introduction

Diet modeling has been widely used in the last decades to assess nutritional recommendations and dietary guidelines. Mainly based on Linear Programming (LP), those models aim at characterizing optimal diets optimizing an objective function (e.g., minimizing diet cost) subject to a set of constraints (e.g., nutritional requirements). The main rationale for the use of such models is that they help solve complex problems that arise because individuals need nutrients but eat foods, and, as nutrients are not evenly distributed in foods, there exists a large variety of possible dietary patterns compatible with a given set of nutritional requirements [1].

LP models have been used for different purposes in nutrition and public health [1]: assessment of the difficulty of complying with and compatibility of various nutrient- and food-based recommendations [2–5]; characterization of least-cost diets meeting a list of nutritional requirements [6]; translation of nutrient recommendations into food plans [7].

An important drawback of LP models, however, is that they may produce unrealistic diets as they fail to capture consumers' preferences [8]. Hence, Henson [6] for the UK and Conforti and D'Amicis [9] for Italy found that it was possible to compose healthy diets which cost only 20 to 30% of observed cost and were composed of a very small number of food items. These results imply that food choices are not driven solely, or even mainly, by the satisfaction of nutritional needs [10,11] but that many other considerations come into play. Thus, models based only on nutritional aspects may produce diets that are incompatible with consumer preferences, which obviously cover many other characteristics of food products and diets.

These problems have been recognized in the research literature and partially addressed through the addition of palatability and social acceptability constraints. A real progress has been to consider, as a starting point of the analysis, the self-selected diets observed in representative samples of the population, and use objective functions such as the minimization of departure from those currently observed dietary patterns [12–16]. This approach relies on the idea that observed food choices reveal consumer preferences and the underlying trade-offs, for instance between palatability and costs, which influence consumers' decisions [17]. Preferences changing only slowly, large departure from observed diets seem unrealistic [14].

However, even within this improved framework, the objective function of the programming problem remains arbitrary, which implies that the substitution possibilities among foods are exogenously defined by the modeler and neither theoretically nor empirically grounded. Thus, we argue that the programming models used to date in nutrition and public health to assess dietary guidelines do not integrate consumer preferences in a satisfactory manner, and that such a limitation has important consequences. First, there is little reason to believe that the substitutions among foods simulated by those models (for instance, the change in whole diet induced by a rise in fruits and vegetables (F&V) consumption) reflect the behavioral adjustments that would be made by"real" consumers. Second, LP models do not allow estimation of the full cost of dietary changes induced by the adoption of recommendations. This cost is not only financial, i.e. due to the change in expenditure to adopt the optimized diet, as it also includes the loss of well-being (or utility) created, at least in the short term, by the decision to comply with new dietary guidelines by consuming less preferred foods ("I decide to eat more broccoli to comply with the '5-a-day' rule, although I do not like broccoli much"). This short-term loss of hedonic rewards from a dietary adjustment is henceforth referred to as a taste cost. Third, as they do not permit calculation of taste costs, LP models cannot support the normative analysis of dietary recommendations, for instance by applying the cost-benefit or cost-effectiveness techniques widely used to assess the social desirability of treatments, drugs and other components of health care systems. This prevents a ranking of alternative recommendations, as well as an assessment of the social desirability of investing more or less in their promotion.

Overcoming those limitations appears to be a relevant challenge for nutrition and public health. Many studies show that standard dietary recommendations, for instance related to F&V, soft drinks, or snacks, are poorly adopted in many countries, especially among disadvantaged and less educated people [18–21]. This low level of compliance with nutritional recommendations might be explained by food prices and budgetary constraints [22], or nutrition knowledge [23], but we argue that it is also, and perhaps mainly, due to the cost that compliance imposes on consumers in terms of taste and convenience.

Hence, the goal of this article is to propose a new modeling approach to quantify this taste cost and identify dietary recommendations compatible, as much as possible, with consumers' preferences. In effect, our contribution addresses, at least partially, the challenge recently formulated by Webb and Byrd-Bredbeener [11] to overcome consumer inertia to dietary guidance by "giv[ing] consumers control with nutrition messages that are realistic, positive, easy to understand, and actionable without an expectation that consumers will surrender foods they love". Our diet modeling method is based on the economic theory of the consumer and parameterized using micro-level data on real food purchases in France. As it is paramount to propose simple messages to consumers, we simulate and compare the impacts of different food-based recommendations. Finally, we perform a cost-benefit analysis to establish how different recommendations should be prioritized.

Methods and Data

The formulation and promotion of dietary recommendations remains the most popular policy instrument to induce consumers to make healthier food choices [24]. Yet the effect of such recommendations and their effect on social welfare is difficult to identify ex-ante. Our research seeks to develop and apply a tool to fill this knowledge gap [25]. To do so, we have developed a three-step methodology:

1. An economic-behavioral model predicts how whole diets would change if consumers complied with a given recommendation; for example to consume more F&V.
2. An epidemiological model estimates the number of deaths avoided (DA) due to the dietary change.
3. A cost-benefit assessment of the recommendation is carried out by balancing the taste cost of compliance with the recommendation and the policy cost of inducing consumers to change their behaviours against the monetized value of the health benefit from improved diets.

The economic model of diet choice

The standard economic theory of consumer behaviour assumes that an individual chooses the amounts of goods she is going to consume in order to maximise a function–named"utility"—subject to a budget constraint. The utility function describes the preferences of a consumer which, in the case of food choices, relate to the taste of the goods, their convenience, and many other attributes. The budget constraint takes into account the prices of goods and available income. This optimisation program is referred to as the"nutritionally unconstrained problem". Its solution, in the case of food choices, defines which goods are eaten and in which quantities. In this context, the adoption of a nutritional recommendation, such as eating a minimum quantity of F&V per day, is conceptualized as the integration of an additional constraint in the previous program. The additional constraint leads the consumer to modify her choices in order to comply with this new constraint and thus choose a modified set of goods (or the same goods but in different quantities). We call this new optimisation program the"nutritionally constrained problem". Comparison of the solutions of those two programs provides two key results:

- First, the impact of the adoption of a nutritional recommendation on the entire diet, and hence a full characterization of the substitutions among foods that the recommendation has induced.
- Second, an estimate of the loss of utility, or taste cost, that the consumer incurred in the short term by adopting the nutritional recommendation. Adoption always reduces utility of the consumer because, if it was not the case, the consumer would have complied with the recommendation in the unconstrained situation.

An empirical difficulty arises because the utility function is not observed. However, assuming rational behavior as is standard in most analyses of consumer choices, observed consumption, given market prices and income, is just the solution of the"nutritionally unconstrained program". This property is used to infer preferences from actual consumption data. Once the utility has thus been revealed and summarized in the form of price and income elasticities, economic theory is used to determine how a nutritional constraint affects choices and utility. To get the intuition of how the model works, let's imagine a change in prices. We know that the rational consumer would adjust her consumption as a result of those price variations, and that this response is empirically quantifiable. When we simulate changes in consumption induced by compliance with a nutritional recommendation, prices are held constant, but we fall back on the economic framework by introducing "shadow prices", defined as the set of prices that would have to prevail for the nutritionally-unconstrained individual to choose the exact same bundle of goods as the nutritionally-constrained individual. In other words, if the shadow prices were the current market prices, the consumer would spontaneously conform to the nutritional recommendation. For instance, the shadow price of red meat for the recommendation to decrease red meat consumption by 5% is the increase in the price of red meat that would be necessary for consumers to adopt the recommendation, all else being held constant. The difference between market price and shadow price would in that case be negative and akin to a price tax that would discourage consumption of red meat. Moreover, the shadow price differs from the market price for any food item which contains red meat (e.g. ready meals). However, because consumers substitute foods with one another, the optimal solution that minimizes the utility cost of complying with the recommendation also involves changes in all the foods that may substitute or complement red meat consumption. The economic theory then generates important insights:

- For any given food, the wedge between shadow price and market price is proportional to the per-unit nutritional contents (e.g. contents in F&V) of the goods appearing in the nutritional constraint (e.g. an increase in F&V consumption), and depends on demand elasticities. Shadow prices are thus empirically computable.
- From the set of shadow prices, we can deduce the change in consumption for each good. In particular, compliance with a nutritional constraint induces broad changes in the diet, even for those goods that do not appear directly in the constraint, because of relationships of substitutability and/or complementarity with the goods entering the constraint. That is to say that, for example, meat consumption might be affected by a recommendation to increase F&V consumption. This relationship of substitutability or complementarity between goods is expressed by the cross price elasticities of demand in the initial unconstrained situation. For example, the cross price elasticity of meat demand with respect to the price of fruits measures

the responsiveness of meat demand to a change in the price of fruits. Hence, if we are able to estimate the price elasticities describing the behavior of the unconstrained individual, it is possible to infer the dietary adjustments resulting from compliance with the nutritional recommendation. We note that such elasticities, based on econometric analyses of food demand, are often used to assess the impacts of a nutritional tax on food choices [25]. Compared to these approaches developed to assess the effect of price variations on consumption and nutrient intakes, in this paper we consider the dual problem which consists of determining the price system and the compensation value such that a nutritional recommendation can be adopted without loss of utility.

- The taste cost of complying with a nutritional constraint is measured by the"compensating variation" (CV) of the dietary adjustment, defined as the amount of additional money a household would need to reach its initial utility after complying with the recommendation. The CV is calculated as the difference between observed expenditure (the food budget in the unconstrained situation) and the corresponding expenditure (i.e., food budget) that would be necessary to hold utility to its initial level when the nutrition constraint is imposed. This taste cost should be interpreted as a measure of the short-term loss of utility of the consumer which is a way to evaluate how costly/difficult it is to deviate from the unconstrained situation, ignoring the long-term health benefits of compliance, which are considered separately in the analysis (i.e., their measurement in terms of deaths avoided is presented in the next section and their valuation is discussed in the "Cost-benefit" section).

The theoretical and mathematical backgrounds of the model are presented in greater detail elsewhere [25].

Health impact assessment

The health effects of consumption changes induced by the adoption of a nutritional recommendation are assessed with the DIETRON model. The DIETRON model provides estimates of the number of deaths avoided due to diet-related chronic diseases. As explained by Scarborough et al. ([26], p. 711):"the DIETRON model uses age- and sex-specific estimates of relative risk drawn from meta-analyses of trials, cohort studies and case–control studies, to estimate the impact on chronic disease mortality of counter factual population dietary scenarios". The inputs of the DIETRON model are changes in intakes of the following foods and nutrient: fruits, vegetables, fibers, total fat, monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA), saturated fatty acids (SFA), cholesterol, salt, and energy. The exact pathways to specific diseases (e.g., stroke) and intermediate risk factors are described in the paper that first presented the model [27]. The studies covered by the meta-analysis of risk factors are clearly listed in Table 1 of the same reference, while the relative risk ratios used in DIETRON are published in Table A2 of the Appendix of reference [26].

The output of the economic model is a vector of changes in consumption of goods when the consumer conforms to a nutritional recommendation. To link it to DIETRON, we use a composition table that provides for each good its content in the different foods and nutrients entering the DIETRON model.

Cost-benefit analysis

The overall effect of each recommendation on social welfare is established by comparing the monetary value of its costs and benefits. In this framework, the expressions"welfare improving" and "cost-beneficial" refer to situations where the health benefits outweigh the costs as defined in this section. The long-term health benefit from compliance with a recommendation is

Table 1. Changes in food consumption induced by the imposition of dietary constraints (right percentage in each column) and baseline contribution of each food group to the constrained food (left percentage in each column) for the "Lower-average" consumer type.*

	F&V +5%		Red meat -5%		All meats -5%		Salty/Sweet fat prod. -5%		Soft drinks -5%		Milk prod. +5%		Butter, cream & cheese -5%		Fish & seafood +5%	
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Red meat	0.0	-9.1	89.7	-5.5	22.7	-8.2	0.0	2.1	0.0	0.3	0.0	-1.5	0.0	0.6	0.0	-0.9
Other meats	0.0	6.2	0.0	0.7	38.8	-6.4	0.0	3.4	0.0	0.4	0.0	0.1	0.0	7.0	0.0	-0.1
Cooked meats	0.0	-3.3	0.0	0.8	32.2	-1.3	0.0	-2.4	0.0	-0.1	0.0	-1.1	0.0	0.8	0.0	-0.2
Meat aggregate	*0.0*	*-0.3*	*89.7*	*-0.7*	*93.7*	*-5.2*	*0.0*	*1.2*	*0.0*	*0.2*	*0.0*	*-0.6*	*0.0*	*3.6*	*0.0*	*-0.3*
Milk products	0.0	-4.3	0.0	0.7	0.0	3.3	0.0	1.2	0.0	0.5	100.0	5.0	0.0	-0.9	0.0	0.0
Cheeses, butters, fresh creams	0.0	-2.9	0.0	0.1	0.0	4.2	0.0	-4.8	0.0	-0.1	0.0	0.2	100.0	-5.0	0.0	0.1
Dairy pdts	*0.0*	*-4.0*	*0.0*	*0.6*	*0.0*	*3.4*	*0.0*	*0.0*	*0.0*	*0.3*	*100.0*	*4.1*	*100.0*	*-1.7*	*0.0*	*0.0*
Fish	0.0	9.7	0.0	1.7	0.0	7.5	0.0	2.4	0.0	0.1	0.0	0.2	0.0	-0.8	96.1	5.3
Eggs	0.0	-7.6	0.0	-0.8	0.0	-3.3	0.0	1.3	0.0	0.5	0.0	-0.7	0.0	-9.8	0.0	-1.0
Animal products	*0.0*	*-2.3*	*89.7*	*0.3*	*93.7*	*1.1*	*0.0*	*0.5*	*0.0*	*0.3*	*0.0*	*2.4*	*0.0*	*-0.5*	*96.1*	*0.2*
Grains	0.2	-6.2	0.0	-1.0	0.0	-0.3	0.0	-3.2	0.0	-0.2	0.0	-2.3	0.0	-3.2	0.0	-1.4
Potatoes	0.0	-27.6	0.0	-0.8	0.0	-4.5	0.0	4.5	0.0	-1.5	0.0	-1.2	0.0	8.5	0.0	-1.0
Starchy food	*0.2*	*-16.1*	*0.0*	*-0.9*	*0.0*	*-2.2*	*0.0*	*0.4*	*0.0*	*-0.8*	*0.0*	*-1.8*	*0.0*	*2.2*	*0.0*	*-1.2*
Fruits—Fresh	40.7	-1.1	0.0	1.5	0.0	2.7	0.0	-1.8	0.0	0.3	0.0	-0.4	0.0	-3.3	0.0	1.0
Fruits—Processed	2.8	27.0	0.0	0.2	0.0	-3.2	0.0	3.6	0.0	1.0	0.0	-5.2	0.0	-8.3	0.0	-0.5
F&V juices	6.3	4.0	0.0	0.8	0.0	-0.3	0.0	7.9	0.0	0.8	0.0	-1.8	0.0	-0.6	0.0	0.4
Vegetables—Fresh	32.6	9.5	0.0	-0.5	0.0	-0.3	0.0	0.0	0.0	0.1	0.0	0.4	0.0	6.7	0.0	0.0
Vegetables—Processed	9.9	18.4	0.0	0.0	0.0	-2.7	0.0	1.5	0.0	0.5	0.0	-1.6	0.0	4.4	0.0	-0.4
Fruits—Dry	0.5	-6.0	0.0	1.4	0.0	11.7	0.0	2.7	0.0	-1.7	0.0	6.6	0.0	-2.5	0.0	1.5
F&V aggregate	*92.7*	*5.9*	*0.0*	*0.5*	*0.0*	*0.8*	*0.0*	*-0.5*	*0.0*	*0.3*	*0.0*	*-0.3*	*0.0*	*1.1*	*0.0*	*0.4*
Ready meals	4.2	-11.7	10.1	-1.1	6.3	-3.6	0.0	-1.6	0.0	-0.6	0.0	-1.3	0.0	1.4	3.8	-2.9
Oil, margarine, condiments	0.0	12.0	0.0	0.1	0.0	-1.2	0.0	11.1	0.0	0.4	0.0	1.0	0.0	9.3	0.0	0.1
Salt-fat products	0.0	-20.7	0.1	1.2	0.1	10.3	8.1	-8.5	0.0	-1.4	0.0	-2.7	0.0	-28.5	0.0	-0.3
Sugar-fat products	2.9	2.1	0.0	0.1	0.0	0.3	91.9	-4.7	0.0	0.2	0.0	-0.2	0.0	-2.7	0.0	-0.2
Soft drinks	0.0	-18.4	0.0	0.7	0.0	5.3	0.0	2.8	100.0	-5.0	0.0	-3.5	0.0	-3.2	0.0	-0.1
Water	0.0	-20.0	0.0	1.8	0.0	10.0	0.0	-0.7	0.0	-0.2	0.0	-0.2	0.0	3.0	0.0	0.1
Alcoholic beverages	0.0	12.9	0.0	0.3	0.0	-0.4	0.0	3.7	0.0	-0.2	0.0	0.2	0.0	1.6	0.0	-0.5

* Food groups are defined as in [29]: Red meat (beef and veal); other meats (poultry, pork, lamb, etc.); cooked meats (ham, pâté, sausages, bacon, etc.); milk products (milk, yoghurt, dairy desserts, etc.); cheese, butter and cream; fish and seafood; eggs; grain products (bread, pasta, rice, wheat flour, and cereals); potatoes; fresh fruits; processed fruits (canned & compote); fruits & vegetables juices; fresh vegetables including legumes; processed vegetables including legumes (canned, frozen); dried fruits & nuts; ready meals (pizza, sauerkraut, cassoulet, etc.); oils & vegetable fat; salt-fat products (finger food, chips, crackers, appetizers); sugar-fat products (candy, chocolate, cookies, pastry, ice cream, jam, etc.); soft drinks (sodas, lemonade, syrups, etc.); mineral and spring waters; alcoholic beverages.

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monetized by multiplying the number of DA, calculated from the health impact assessment outlined in the previous section, by the value of a statistical life, which is interpreted as the effort, in terms of the resources used, that society is willing to make in order to reduce the risk of death [28]. On the cost side, the short-term taste cost imposed on consumers, which was discussed above in the presentation of the economic model, represents a first component. However, we also need to include the costs of implementation of policies and interventions necessary to bring about compliance with each recommendation. This is important because, while the model calculates the effects of dietary adjustments under an "as if" assumption, i.e.

assuming compliance with the nutritional recommendation, in practice behavioural change requires public investment in social marketing campaigns and other types of interventions.

A problem arises, however, because quantifying the cost of a policy inducing consumers to change their consumption of a given food or nutrient by a certain amount is very difficult. We circumvent the issue by defining a cost-benefit threshold characterizing the maximum amount that could be invested to promote a given recommendation while ensuring that the benefits outweigh the costs. This is achieved by balancing the health benefits generated by a nutritional recommendation (denoted *Bh)* against the cost to individuals (denoted *CC* and measured by the short-term taste costs) and the cost of public sector interventions (C_P). The cost-benefit threshold is then simply calculated as $C_P = Bh–CC$.

Empirical assessment

The empirical implementation of the economic model requires different sets of data. To determine the initial consumption of foods and the economic parameters (elasticities), we use the source of data and results of the most recent available econometric analysis of food demand in France conducted by Allais et al. [29]. That study is based on data from a representative panel of French households (KANTAR Worldpanel) over a five-year period from 1996 to 2001. The participating households record weekly all their purchases of foods, using bar code scanning technology whenever possible, but foods without bar codes are also recorded. The information provided includes the characteristics of the purchased product (e.g., brand, size), the quantity purchased as well as related expenditure. KANTAR also provides the main socio-economic characteristics of the panel households, including household size, region of residence and income class. Each annual round of the data set contains information on approximately 5,000 households, with an annual rotation of roughly one third of the participants.

For the sake of consistency, we had to use the same 22 product aggregates as study [29] from which the elasticities are drawn. Those elasticities in [29] are reported for four representative types of households differentiated by income quartiles and labeled in what follows as "Modest", "Lower average", "Upper average", and "Well-off". The nutrient contents of the 22 food aggregates are calculated by combining the food composition database of the French dietary intake survey INCA2 and average adult intakes of the component foods of each aggregate drawn from INCA2 (which stands for "Étude Individuelle Nationale des Consommations Alimentaires 2006–7"), which are freely available from the open data platform of the French government (https://www.data.gouv.fr/fr/datasets/donnees-de-consommations-et-habitudes-alimentaires-de-letude-inca-2-3/). The model is applied to estimate the variations in households' purchases induced by the adoption of eight food-based recommendations taken one at a time. We provide some details about the choice of recommendations at the beginning of the results section. The effects of dietary adjustments are calculated under an "as if" assumption, i.e. assuming that the households comply with a 5% change in the constraint level (for example in the case of F&V, we assume that a consumer has to increase his consumption of F&V by 5%).

To simulate the health effects, changes in food purchases at household level, as calculated by the economic model, are translated into changes in individual intakes, distinguishing between males and females and using the INCA2 dietary intake database. This is accomplished under the assumption that (i) all household members experience the same relative changes in intakes, and (ii) the relative changes in consumption of food-at-home and food-away-from-home are equal. Variations in nutrient intakes are then calculated from variations in food intakes by using the nutritional coefficients of the 22 aggregates. Finally, the changes in nutrients are fed into DIETRON model so as to estimate the health effects of the dietary adjustments.

The parameters of the DIETRON model are derived from world-wide meta-analyses of dietary risk factors and are not country specific, so that adapting the DIETRON model to France only requires calibration of the initial mortality levels, by relevant causes. This is achieved by using the INSERM data on mortality in France attributable to major diet-related diseases (INSERM stands for "Institut National de la Santé et de la recherche Médicale"). We limit the study to individuals between the age of 25 and 74 and therefore focus on the effects of dietary changes on premature deaths. The chronic diseases considered in DIETRON account for slightly more than one third of total French mortality.

Finally, the health benefit is quantified by applying a monetary value to the reduced mortality figures calculated by DIETRON. Estimates of the value of a statistical life vary substantially across countries and policy domains. In the following analysis, we use a conservative value of a statistical life, based on the cost threshold of a Quality Adjusted Life Year that is applied in the UK to investigate the cost-effectiveness of medical care (e.g., drugs, procedures). As explained in Irz et al. [25] this provides a value ranging from €240k to €360k.

In addition to the mean value of the different relative risks, the DIETRON model also provides the distributions of each relative risk parameter. Twenty-six of those follow log-normal distributions and six follow normal distributions, while all are independent. We perform Monte Carlo simulations by drawing a set of parameters one million times. To be more precise, for a given type of consumer, we draw a set of 32 parameters, use this set to evaluate the number of DA for each nutritional recommendation and repeat the operation one million times. In the results section, we provide the median as well as the 2.5 and 97.5 percentiles of DA for each recommendation.

The R codes to simulate both the economic model and the epidemiological model are available upon request from the authors.

Results

Comparison of our data describing the average diet of French consumers with conventional dietary norms confirms previous findings that the French diet is rich in fat, particularly of the saturated kind that originates primarily from animal products [14,15]. This justifies the analysis of three food-based recommendations aimed at reducing consumption of: all meats; red meat, because of its particularly high content in saturated fatty acid (SFA); and SFA-rich dairy products, which include butter, cream, and cheese. On average, intake of calcium in the French population complies with dietary reference intake, but is too low for some consumer groups (mainly women and the low-income). This shortcoming could be addressed by raising consumption of the other dairy products (henceforth referred to as "milk products"). Snacking has also been identified in France as a potentially growing issue, particularly among young consumers [30], and we therefore consider recommendations to reduce consumption of both salty and sweet snacks (henceforth referred to as "salty/sweet-fat products"). Sugar-sweetened beverages are increasingly recognized as an important determinant of body weight [31] and a recommendation to reduce their consumption is appropriate in France given concerns over obesity and overweight in the population. Consumption of F&V falls well below the recommended five portions a day, and this is particularly true for low-income consumers. A F&V recommendation is therefore included. Finally, there is moderate but consistent evidence regarding the health benefits of increased fish consumption [32], and we therefore analyse the impact of a related recommendation.

Table 1 presents the simulated dietary adjustments for the "lower average" household type. Although results for the other types are not reported here, we have found that they are broadly similar to those presented below. This similarity in the way the four household types respond to recommendations is explained by small differences in the price and income elasticities of those household types. Those elasticities, which we used to calibrate the model, are reported in Tables 6–10 of the supplementary material of reference [29]. For each constraint, presented in a separate column, Table 1 depicts first the baseline contribution of each food group to the constrained food, then the consumption changes that would result from compliance with the constraint.

Turning to the changes in diet and focusing first on the"all meats" recommendation, we note that the five percent decrease that is imposed exogenously corresponds to an absolute decline of roughly eight grams per day. This quantitatively small reduction in meat consumption triggers relatively important dietary adjustments. Starchy products are complements of meats and thus their consumption decreases with the reduction in meat consumption (-2.2%). On the contrary, dairy products, which provide proteins, are meat substitutes and thus their consumption increases with the exogenously-imposed reduction in meat consumption (+3.4%). Looking at the results at a lower level of product aggregation reveals that complex adjustments also take place within broad food categories. Thus, consumers choose to compensate the decrease in meat consumption by raising consumption of fish (+7.5%) but also, and less expectedly, by reducing that of eggs (-3.3%).

To avoid confusion in interpreting the results, we note that the decrease in consumption of the "Meat aggregate" category is different from 5% (the target for a decrease in total consumption of meat). This is because a food category (ready meals) also contains some meat. Then, the change in "All meats" consumption takes into account the changes in consumption of the "Meat aggregate" as well as the changes in the consumption of the other food categories which contain some meat. This remark applies to other recommendations (e.g., on F&V).

The dietary adjustments induced by compliance with the constraints are heterogeneous. Compared to simulated adjustments for the"all meats" constraint, imposition of the constraint on red meat produces smaller consumption changes. This is understandable as this constraint is less demanding in the sense that it restricts a smaller fraction of the diet (the decrease in red meat consumption is about 3 g/day) and substitution with other meats occurs leading to a small decrease in aggregate meat consumption (-0.7%). Overall, the "red meat" constraint affects consumption of the different food groups in the same direction as, but with a lower magnitude than, the "all meat" constraint.

The recommendation to increase consumption of F&V by 5% induces the largest adjustments in the diet. Thus, consumption of starchy products (-16.1%), dairy products (-4.0%), ready meals (-11.7%), oil and margarine (+12.0%), and salt-fat products (-20.7%) are strongly affected. Within the F&V category, and in terms of absolute quantity, the biggest increase is for fresh vegetables whereas fresh fruit consumption decreases by a very small amount. However, the largest percentage increases are for processed products, meaning that the adoption of the recommendation raises the relative importance of processed products within the F&V category. Regarding the other recommendations, it is worth noting that an increase in consumption of milk products leads to a decrease in consumption of meat (particularly red meat), starchy products, and salt-fat products. A decrease in consumption of butter-cream and cheese induces an increase in consumption of meat, particularly "other meats", oil and margarine, and starchy products; it also results in a (large) decrease in the consumption of salt-fat products. An increase in fish consumption leads to a decrease in consumption of ready meals, starchy foods, and red meat. A decline in consumption of salt/sweet-fat products leads to an increase in oil and margarine consumption and a decrease in consumption of cream-butter and cheese. Finally, a decrease in consumption of soft drinks has a relatively small impact on consumption of the different food products.

Table 2. Change in the nutritional profile of the diet (whole population).

	F&V +5%	Red meat -5%	All meats -5%	Salty/Sweet fat prod. -5%	Soft drinks -5%	Milk prod. +5%	Butter, cream & cheese -5%	Fish & seafood +5%
	Percentage variations (%) in nutritional factor/indicator							
DIETRON nutritional factors (units)								
Fruits (g)	1.73	1.11	1.84	-0.85	0.36	-0.76	-3.20	0.67
Vegetables (g)	7.04	-0.47	-1.29	-0.03	0.07	-0.19	5.39	-0.54
Fibers (g)	-2.32	-0.24	-0.33	-1.86	-0.13	-0.98	-0.36	-0.67
Total Fat (% energy)	1.40	0.11	0.12	1.47	0.10	0.52	1.04	0.21
MUFA (% energy)	2.57	0.10	-0.32	3.13	0.15	0.58	2.25	0.22
PUFA (% energy)	4.66	0.23	-0.06	5.09	0.12	0.61	3.06	0.41
SFA (% energy)	-0.35	0.11	0.85	-1.20	0.07	0.54	-0.81	0.19
Cholesterol (% energy)	-0.82	-0.09	-1.00	-0.46	0.18	0.18	-1.22	0.20
Salt (g)	-5.13	-0.23	0.30	-2.84	-0.23	-1.06	-2.65	-0.78
Energy (MJ)	-2.35	-0.23	-0.30	-0.85	-0.10	-0.49	-0.76	-0.55
Other nutritional indicators (units)								
Energetic density (kcal/100g)	-0.76	-0.13	-0.13	-0.21	-0.02	-0.17	-0.71	-0.16
Proteins (g)	-3.06	-0.46	-1.14	-0.87	0.00	-0.32	-0.06	-0.34
Available carbohydrates (g)	-4.49	-0.29	-0.11	-2.40	-0.22	-1.06	-2.01	-0.81
Lipids (g)	-1.03	-0.12	-0.16	0.59	0.00	0.03	0.26	-0.33
Ca (mg)	-4.92	0.23	2.42	-1.93	0.00	0.81	-1.25	-0.28
Fe (mg)	-2.08	-0.34	-0.72	-1.00	-0.06	-0.69	-0.04	-0.52
K (mg)	-3.56	-0.01	0.09	0.15	-0.07	-0.10	1.04	-0.24

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Next, variations in consumption for the four consumer types are translated into changes in intakes, and Table 2 summarizes the results for the whole population. Complex adjustments in the nutrient profile of the diet occur, and the overall effect on diet quality is ambiguous. Thus, in most case there are nutritionally beneficial changes but also adverse ones. For most recommendations, positive changes in the diet relate to lower intakes of salt and energy intake, and a decrease in energy density. Adverse effects, however, are also evident. For example, for all recommendations, fiber intake decreases and total fat intake rises. Five recommendations (on"all meats","red meat","soft drinks","milk products", and"fish and seafood") have relatively small impacts on nutrient intakes, i.e. lower than one percent (in absolute value) for most nutrients. Recommendations on the consumption of"salty/sweet-fat products", and"butter-cream and cheese", have larger impacts, as the changes in the intake of some nutrients are larger than one percent (in absolute value). The recommendation on F&V induces much larger changes, often in excess of two percent (in absolute value). It is worth noting large reductions in intakes of energy, salt and carbohydrates, and that some changes seem counter-intuitive. For instance, the increase in F&V intake leads to a decrease in fiber intake. This is caused by multiple substitutions within the diet, especially the reduction in consumption of grains, potatoes and ready meals induced by compliance with the F&V constraint. We can also note a reduction in iron intake mainly due to a reduction in consumption of grains, potatoes, meat, ready meals; a reduction in potassium intake attributable to a decrease in consumption of potatoes, ready meals and dairy products; and a reduction in calcium intake caused by a drop in consumption of dairy products, ready meals and water.

Regarding the public health impacts, it is reassuring that every nutritional recommendation reduces the mortality due to chronic diseases. Table 3 displays the results of Monte-Carlo simulations in terms of DA. There is some correlation between the relative magnitude of variations in nutrient intakes and the number of DA. Thus, the recommendation on F&V, which induces the largest changes in nutrient intakes, has by far the largest impact on mortality, as it might save as much as 2507 (2228–2790) DA per annum, which is about 3.8% of the total number of deaths taken into account in the DIETRON model. Recommendations on"salty/sweet-fat products" and"butter-cream-cheese" have intermediate impacts on the number of DA (569 (479–662) and 696 (551–838), respectively), although it would have been difficult to rank the health impacts of those two constraints on the sole basis of the changes in nutrient intakes. Finally, the other recommendations save less than 400 DA (median value). Among those, the recommendation on"fish and seafood" has the largest impact and the recommendation on soft drinks the smallest. It should be acknowledged that the rather small impact on health of lowering soft drink consumption might be explained by the relatively small average consumption in the French adult population. For instance, a recent study [33] reported that sales of sugar-sweetened beverages in France were among the lowest among EU countries, at about 52 calories sold per capita per days, as compared to almost twice that amount in Germany and more than three times that level in the USA. This example highlights the need to use caution when generalizing our conclusions to other countries because differences in country-specific contexts matter to health outcomes, as claimed with reference to taxation of soft drinks by other authors [34].

Conversely, the recommendation on fish and sea food has a surprisingly large effect if one takes into account the rather small change in consumption that is imposed (the 5% rise is worth 2g/day). It is partially due to the decrease in consumption of meat and ready meals.

It is also interesting to note that the two recommendations to limit meat consumption have about the same impact on health whereas the changes in nutrient intakes induced by a decrease in red meat consumption are much lower than those induced by the decrease in meat consumption. The main reason is that the"all meats" recommendation leads to a much stronger increase in consumption of"cheese, butter, cream" and salt-fat products.

On average, about 35% of DA is attributed to coronary heart disease (CHD), 20% to strokes and 45% to cancers. This is linked to the initial number of deaths due to each of the three groups of non-communicable diseases (NCD) considered here. Some recommendations have, however, a relatively larger impact on CHD ("salty/sweet-fat products","cream-butter and

Table 3. Health effects of the simulated dietary adjustments (DA: deaths avoided).

	F&V +5%	Red meat -5%	All meats -5%	Salty/Sweet fat prod. -5%	Soft drinks -5%	Milk prod. +5%	Butter, cream & cheese -5%	Fish & seafood +5%
DA for DIETRON diseases	2,507	230	245	569	118	251	696	395
(95% confidence interval)	(2228–2790)	(198–261)	(193–298)	(479–662)	(106–131)	(199–305)	(551–838)	(342–449)
% CHD	34	28	21	44	28	36	44	35
% Stroke	17	19	22	21	19	26	12	20
% Cancers	49	53	57	35	53	38	44	45
Share (%) of mortality avoided								
Modest & Lower average	4.54	0.33	0.26	0.69	0.18	0.41	0.88	0.56
Upper average & Well-off	2.69	0.38	0.54	1.11	0.17	0.33	1.33	0.65

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cheese”) whereas others have a relatively larger impact on cancers (”F&V”,”red meat”,”all meats”).

In order to investigate equity effects, Table 3 also displays the share of mortality avoided separately for low-income consumers, defined by an income less than the median, and high income consumers (defined symmetrically). It should be acknowledged that the prevalence of diet-related chronic diseases among the low-income is higher than that in higher income categories, which is explained in part by less healthy consumption patterns. A reduction in health inequity is, however, not achieved by all the recommendations. The F&V recommendation and, to a lesser extent, the milk products recommendation, induce a reduction in health inequity as the share of avoided mortality is relatively larger among the low income. The other recommendations increase health inequity, with the exception of the recommendation to reduce consumption of soft drinks, which is neutral from that point of view.

It may first seem surprising that while the relative dietary adjustments are largely similar across the four income groups, the health effects vary significantly. This is explained by the fact that, in addition to those dietary adjustments, the health effects depend also on the initial diets and initial mortality levels by type of diet-related diseases, which differ across the four income groups.

The taste costs borne by consumers are clearly linked to the magnitude of the dietary changes induced by the adoption of the recommendations and can be large (Table 4). Thus the 5% increase in F&V consumption imposes a high taste cost (€466 million) when compared to other recommendations. That recommendation has the largest health effect but is also costliest to consumers. By comparison, the red meat, soft drinks, milk products and fish recommendations deliver small numbers of DA at a very low taste cost. We can then oppose recommendations which have smaller health effects (in terms of DA) but are not costly to consumers (red meat, soft drinks, milk product and fish) and the F&V recommendation which has strong health effects but is costly to consumers. The”all meats” recommendation also appears very costly to consumers. Finally, recommendations on”salty/sweet-fat products” and”butter, cream, and cheese” both generate moderate health gains while imposing moderate taste costs.

Table 5 presents estimates of the cost-benefit threshold C_p defined as the maximum amount that could be invested to promote a recommendation while ensuring that the outcome remains cost-beneficial (i.e., the health benefits, measured by the monetary value of DA, outweigh the policy and taste costs). Using very conservative assumptions to value health, it turns out that, except for the”all meats” recommendation, this budget threshold is much larger than what is typically used to design and run information campaigns. For instance, Capacci and Mazzocchi [35] report that the ambitious “5-a-day” UK campaign to encourage consumption of F&V, which was partially successful since it raised consumption by 8%, had a total budget of less than £3 million (roughly €4 million). Thus, if one believes that a population-wide intervention

Table 4. Health benefits and taste cost of the dietary adjustments (median and 2.5 and 97.5 percentiles derived from Monte Carlo simulations).

	F&V +5%	Red meat -5%	All meats -5%	Salty/Sweet fat prod. -5%	Soft drinks -5%	Milk prod. +5%	Butter, cream & cheese -5%	Fish & seafood +5%
Taste Cost (M€)	466	10	76	89	1	13	109	10
% food budget	0.64	0.01	0.10	0.11	0.00	0.02	0.14	0.01
DA	2,507	230	245	569	118	251	696	395
(95% confidence interval)	(2228–2790)	(198–261)	(193–298)	(479–662)	(106–131)	(199–305)	(551–838)	(342–449)
% DA (on DIETRON diseases)	3.8	0.3	0.4	0.9	0.2	0.4	1.1	0.6

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Table 5. Monetized benefits, costs and cost-benefit thresholds of the recommendations (1DA = €240k).

Food based recommendations	Health Benefits (M€)	(95% confidence interval)	Taste Cost (M€)	C_p Max Campaign (M€)	(95% confidence interval)
F&V +5%	602	(535–670)	466	136	(68–203)
Red meat -5%	55	(48–63)	10	45	(37–52)
All meats -5%	59	(46–72)	76	-17	(-30 - -5)
Salty/Sweet fat prod. -5%	137	(115–159)	89	48	(26–70)
Soft drinks -5%	28	(25–31)	1	27	(24–30)
Milk prod. +5%	60	(48–73)	13	47	(35–60)
Butter, cream & cheese -5%	167	(132–201)	109	58	(23–92)
Fish & seafood +5%	95	(82–108)	10	85	(72–98)

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achieves the target of 5% change in consumption, the conclusion follows that promotion of most healthy-diet recommendations is socially desirable. Further, the results also give a simple criterion to rank the different recommendations: on the basis of the budget threshold C_p, healthy-eating messages targeting the consumption of F&V as well as fish/seafood should be prioritized. The recommendation on SFA-rich dairy products is likely to perform well too, but there is a larger uncertainty on its impact on health.

Discussion

Recently, the US Dietary Guideline Advisory Committee (DGCA), seeking to assess the desirability of reformulating the 2010 guidelines, concluded that"the overall body of evidence identifies that a healthy dietary pattern is higher in vegetables, fruits, whole grain, low- and non-fat dairy, seafood, legumes, and nuts; lower in red and processed meat; and low in sugar-sweetened foods and drinks and refined grains" [36], Part A, p. 4). These recommendations express clear dietary targets but leave some questions open. Hence, given the current state of consumer preferences, what are the paths of least resistance for consumers to move towards those targets? In other words, which recommendations must be prioritized in order to deliver the largest health benefits while imposing the lowest policy and taste costs? Our analysis provides some important insights about those questions.

First, the simulations conducted on French data reveal that a rational consumer would respond to diet recommendations through large and complex changes in consumption, which implies that an accurate assessment of the health and economic effects of such recommendations requires a whole diet approach. The substitutions in the diet are functions of consumers' preferences for foods, which cannot be established a priori but should be estimated on the basis of observed choices. Further, those adjustments may reinforce the impacts of some recommendations. For instance, the adoption of the F&V recommendation induces other nutritionally-favorable changes, such as a reduction in consumption of meat, ready meals and salt-fat products. However, compliance can also have adverse effects in some nutritional dimensions: the same F&V recommendation leads to reductions in consumption of milk products and intake of calcium. It also results in a reduction in fiber, potassium, and iron intakes. Even if the overall health impacts estimated with the DIETRON model are positive, such results must be taken into account in the design and communication of dietary recommendations, especially for sub-populations with higher risks of nutritional deficiencies. For instance, the decrease in calcium intake induced by the adoption of the F&V recommendation may be detrimental to some sub-groups of the population. Similarly, regarding iron and potassium, we know that intakes by French women are on average below recommended values. In this case, promotion of F&V consumption should ideally be accompanied with messages aimed at limiting the risk of worsening deficiencies in those nutrients (for instance, by not decreasing too much consumption of red meat or dairy products). This also suggests that further research is needed to identify combinations of different constraints best suited to avoid such negative consequences in specific sub-populations.

Second, food-based recommendations studied in this article differ widely in terms of both their health impacts and the taste costs that they impose on consumers. Recommendations to decrease by 5% consumption of red meat and soft drinks, or increase by 5% consumption of milk products and fish/seafood generate moderate taste costs. Conversely, recommendations related to F&V consumption and, to a lesser extent, butter/cream/cheese, salty-sweet fat products, and all meats create larger taste costs. Compliance with the F&V recommendation generates the largest taste-cost, but also, in terms of public health, the largest health benefits (the largest number of DA). The simulations indicate, however, that high budgets could be devoted to promoting F&V while keeping this policy cost-beneficial. More generally, our analysis suggests that allocating more resources to the promotion of several food-based recommendations would be welfare-improving in France.

From a methodological angle, the economic model presented here has two advantageous characteristics over the programming models used to date to investigate diets in nutrition and public health. First, it is based on the economic concept of preferences, which are revealed by consumers' actual choices, and the response of those choices to exogenous changes (e.g., rise in price). This introduces realism when defining preferences and circumvents the difficult problem of imposing palatability and acceptability constraints in an ad-hoc and somewhat arbitrary manner. Second, the explicit consideration of preferences (i.e., utility) into the model makes it possible to estimate the tastecost of compliance with recommendations or, in other words, the reduction in hedonic and other rewards created by compliance with those recommendations.

Another contribution of our approach is to establish a clear link between the economic-behavioural model of food choice under dietary constraints and an epidemiological model quantifying the impact of dietary changes on mortality. This allows us to simulate, within a fully consistent framework, the effect of adoption of nutritional recommendations on short-run hedonic rewards and long-term health for several income groups of the French population. The analysis proceeds further by integrating health and welfare effects into a cost-benefit measure, which permits a ranking and comparison of recommendations.

Our analytical framework complements approaches previously developed in nutrition and public health and based on programming models. Those models can be used to identify dietary targets, following which the economic-behavioural model can be applied to identify cost-beneficial ways of moving towards those targets. However, we must also acknowledge shortcomings of our economic-behavioural approach. First, it is only suitable to assess the effect of marginal (i.e., small) changes. While this is not a problem to decide which types of diet recommendations should be promoted in a given country at a given time, which seems to be the most relevant policy question, the feature also means that we are not able to identify a unique optimal diet. Second, the simulations can only be performed at a relatively high level of product aggregations (i.e., in the range of 20 product groups). Third, as the price elasticties are estimated for consumer groups rather than individuals, they give information on average preferences, which is valid to address public health issues but unsuitable for individual counselling. For example, consider the case of a sub-population of individuals already consuming large amounts of F&V, much larger than the recommendation. First, from a nutritional point of view, as shown in this article, promoting further increase in F&V consumption might have adverse effects, by decreasing iron and potassium intakes, possibly to undesirably low levels. Second, this sub-population might have preferences which strongly differ from those of the average population, reflecting behavioural differences. Applying elasticities estimated for the whole population to this sub-population would then likely produce results and recommendations that are not consistent with their preferences.

We must also acknowledge that the validity of the estimated health benefits and associated policy recommendations depend heavily on the reliability of the DIETRON model. Although that model has been validated and conveys the main aspects of the prevailing consensus in nutritional epidemiology, the lively debate and lack of certainties in that scientific area should be kept in mind when interpreting our results. To illustrate with one example, although a reduction in saturated fat intake remains a key dietary objective in most countries, researchers have started questioning the scientific basis of that recommendation [37,38]. While such issues fall beyond the scope of this paper, they suggest the need to test the robustness of our approach and conclusions by using alternative epidemiological models. Further, the economic model is also subject to uncertainties, which we were unfortunately unable to address as we do not have information about the joint distribution of the elasticity parameters and an assumption of independence of the elasticities would be inconsistent with the theory of the consumer upon which the model is based.

Despite these limitations, the results demonstrate the policy relevance of the approach, showing clear differences in health benefits, taste costs, and benefit-cost balance across recommendations.

We close by pointing out other potential applications of the method to assess recommendations of a different nature, for instance nutrient-based recommendations (e.g., targeting salt), and sustainable recommendations taking into account the environmental impact of diets. It would also be possible to focus on specific nutritional issues by disaggregating food categories (e.g., fatty versus non-fatty fish, processed versus fresh F&V) or to investigate specific consumer clusters of interest. For instance, grouping consumers using criteria other than income would permit to differentiate the impact of recommendations according to age, education, or BMI, the only hard requirement for new applications being the availability of price elasticities congruent with the corresponding food groups and consumer categories. Our analytical framework could also be applied to investigate the impact of recommendations on individuals with healthy initial diets who could be at risk of consuming excessive amounts of foods or nutrients considered “healthy” for the population at large (e.g., F&V). Further research may also compare the benefit-cost balance of food and nutrient-based recommendations in different countries, since that balance depends on country-specific consumption patterns and consumer preferences (as captured by elasticities).

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Author Contributions

Conceived and designed the experiments: XI PL VR LGS. Performed the experiments: XI PL VR LGS. Analyzed the data: XI PL VR LGS. Contributed reagents/materials/analysis tools: XI PL VR LGS. Wrote the paper: XI PL VR LGS.

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