WORKING PAPERS

N° TSE-565

March 2015

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Abstract: *The paper develops a framework combining a model of rational behaviour under dietary constraints, an epidemiological model of diet-related mortality, and a life-cycle-analysis model of environmental impact, which permits the ex-ante assessment of dietary recommendations in multiple sustainability dimensions (i.e., taste cost, welfare effect, deaths avoided, reductions in greenhouse gas emissions and acidification). It is applied to compare in a French context the relative effects and efficiency of six popular sustainable diet recommendations. The results confirm the synergies between the health and environmental dimensions: healthy-eating recommendations usually have a positive effect on the environment, although some exceptions exist. Most of the sustainable diet recommendations appear highly cost-effective, but those most commonly promoted on health grounds (e.g., targeting consumption of salt, fruits and vegetables and saturated fat) rank highest in terms of overall efficiency. Moreover, the valuation of benefits indicates that in most cases health benefits are significantly larger than environmental benefits. Overall, the analysis reveals some under-investment in the promotion of sustainable diet recommendations in France. The general lack of enthusiasm in policy circles for informational measures promoting behavioural change may reflect unrealistic expectations about the speed and magnitude of dietary change rather than an objective assessment of the efficiency of those measures.*

Keywords: food choice; rationing; norms; healthy; nutrition; cost-benefit

Classification: D1; D6; I1; Q5

Highlights :

- We investigate the sustainability effects of promoting dietary recommendations
- We find synergies between the pursuit of health and environmental objectives
- The health benefits from dietary change exceed the environmental benefits
- The promotion of sustainable diet recommendations is highly cost-effective
- Targeting consumption of salt, saturated fat, and fruits/veg. should be prioritized

Welfare and sustainability effects of dietary recommendations

1. Introduction

Food consumption patterns observed in developed countries raise two main types of concerns. First, food production, distribution and consumption accounts for 15 to 30% of total greenhouse gas emissions (GHGEs), thus contributing significantly to climate change (Esnouf et al., 2013). For this reason, dietary changes are often considered an important tool for climate change mitigation (Carlsson-Kanyama and Gonzalez, 2009; Tukker et al., 2011). In high-income countries, many reports recommend promotion of new consumption patterns requiring reductions in meat and dairy consumption and the substitution of plant-based products for animal products (Stehfest et al., 2009; Berners-Lee et al., 2012; Friel et al., 2009).

Second, unhealthy diets, in association with physical inactivity, are risks factors for various chronic diseases, including obesity, strokes, diabetes, and some types of cancers (World Health Organization, 2003). This statement has led many public health agencies to set up prevention policies based on healthy-eating recommendations and information campaigns (Pérez-Cueto et al., 2013). The most common recommendations encourage individuals to adopt healthier diets by consuming more fruits and vegetables (F&V) (Cappacci and Mazzocchi, 2011) and less salt (Shankar et al., 2013). Consumption of starchy foods is also often promoted by public health experts (Mancino et al., 2008), while a decrease in consumption of soft drinks is also encouraged (Jou and Techakehakij, 2012).

However, as noted by Macdiarmid et al. (2012), health and environmental issues need to be tackled together to ensure consistency of the dietary advice delivered to consumers. Although the convergence of health and environmental objectives is not systematic (MacDiarmid et al., 2012; Vieux et al., 2012 & 2013; Masset et al., 2014), it is now widely accepted that a reduction in meat consumption and the shift toward plant-based diets would have a favorable effect on both environment and health (Soret et al., 2014; Aston et al., 2012; Scarboroug et al., 2012).

Indeed, on the one hand, red meat is suspected to have a causal effect on various forms of cancers and may be associated with cardiovascular diseases because of its high content in cholesterol and saturated fat acids (SFA) (McMichael et al., 2007). On the other hand, plant-based products have much lower impacts in terms of GHGEs than animal-based products (Masset et al., 2014).

Whether for health or environmental reasons, consumers are thus increasingly encouraged to choose foods in order to comply with a range of dietary recommendations. Education, information campaigns and food labelling measures are implemented in order to promote adoption of those recommendations. However, a lot of research shows that interventions tend to raise consumers' awareness of nutritional issues without having a large impact on behaviours (Pérez-Cueto et al., 2013).

If several reasons can be proposed to explain the difficulties in changing behaviours, one is related to the "taste cost" of change, that is, the utility loss induced by a dietary change that brings a new balance between long-term health or environmental goals and short-term pleasure and hedonistic rewards (Réquillart et Soler, 2014). In other words, the difficulties in complying with dietary recommendations 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 recommendations.

An important issue is then to determine sustainable diets complying with health and environmental recommendations and compatible, as much as possible, with consumer preferences. In other words, the challenge is to identify dietary recommendations with the potential to improve health and environment but generating the smallest "taste costs" for consumers.

A first group of methods to address this issue builds on linear programming (LP) models which are used to estimate least-cost diets complying with a list of dietary requirements (Henson, 1991; Conforti and d'Amicis, 2000). Such LP models have been recently used by nutritionists to determine optimal diets complying with nutritional or environmental recommendations (Maillot et al., 2010; Macdiarmid et al., 2012; Darmon et al., 2002, 2003, 2006; Srinivasan et al., 2006; Shankar et al., 2008; Arnoult et al., 2010). These methods suffer from important shortcomings because the objective functions and the substitution possibilities among goods are always arbitrarily restricted, and not based on real consumers' preferences.

A second type of approach with a stronger theoretical basis uses empirically-estimated demand systems (Thow et al. 2010, Etilé, 2011, and Eyles et al., 2012). These studies typically estimate price elasticities from demand curves, which are conceptually derived from constrained utility maximization, given prices and a budget constraint. This kind of research has been based on complete food demand systems (e.g. Allais et al. 2010; Briggs et al., 2013; Caillavet et al., 2014), which allows consideration of a large set of interdependent demand relationships. Such methods can support the simulation of impacts of price policies, taxes or subsidies, on food consumption and nutrient intakes. However, compliance with dietary recommendations can only be assessed *ex-post* rather than introduced as constraints in order to determine the price modifications needed to comply with these constraints.

To overcome these limits, Irz et al. (2015) developed a new analytical framework which builds on the microeconomic theory of the consumer under rationing, with the goal of identifying diets compatible with both dietary recommendations and consumer preferences. This framework is built to estimate the substitutions, and overall changes in diet, that would take place if consumers complied with these recommendations. Such a framework is used to assess the difficulty of achieving a given recommendation by identifying the magnitude and nature of the required substitutions in consumption. It also provides the basis for measuring the "taste cost" of complying with a particular nutritional dietary norm, which can then be used in conventional cost-benefit analysis. Compared to the demand system analyses used to assess the effect of price variations on consumption and nutrient intakes, this method considers the dual problem which consists of determining the price system and the compensation value (i.e. the taste cost) such that a dietary recommendation can be adopted without loss of utility.

In the present paper, we use this theoretical framework to empirically estimate the health, environmental and welfare impacts of the adoption of various dietary guidelines by consumers. We consider a set of nutrient-based (salt, SFA), food-based (F&V, meat), and environmentally-based (CO_2 equivalent, $C0_2e$) dietary recommendations, determine the substitutions within the consumers' diet induced by their adoption, and estimate the loss of welfare induced by these changes. To deal with the health issue, we match the economic model with an epidemiological one, and assess the health impacts of diet changes in terms of the prevalence of chronic diseases and associated mortality. Similarly, to deal with the environmental issue, we estimate the effects of the dietary changes on environmental indicators. By combining consumers' taste costs with health and environmental effects, we finally develop a cost-effectiveness analysis of dietary recommendations.

In the next section, we briefly present the theoretical model. In section 3, we present the data and the empirical methods used to simulate the impact of various dietary recommendations on diets, welfare, health and the environment. In section 4, we present the empirical results while section 5 concludes the paper.

2. The Behavioural Model

The main building block of the analysis is a model of dietary adjustment under nutritional and/or environmental constraints (henceforth simply referred to as "dietary constraints"), which was first proposed to investigate the economics of nutritional recommendations by Irz et al. (2015). Making the assumption that the environmental impact of food consumption is linear in the quantities consumed, as is implicit in life-cycle analysis (LCA, Ekvall et al., 2007), extension of the model to the environment sphere is methodologically straightforward. Formally, we assume that an individual chooses to consume *H* goods in quantities $x=(x_1,\ldots x_H)$ to maximize a strictly increasing, strictly quasi-concave, twice differentiable utility function $U(x_1,\ldots x_H)$, subject to a linear budget constraint $p.x \leq M$, where *p* is a price vector and *M* denotes income. However, departing from the standard neoclassical model, we now assume that the consumer operates under *N* additional linear constraints. Those constraints could, for instance, correspond to a maximum permissible level of CO_2e from the diet, a maximum consumption of meat, or, in the nutrition domain, maximum levels of consumption of "unhealthy" nutrients (e.g. salt, SFA). Denoting by a_i^n 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 databases or food composition tables, the dietary constraints are expressed by:

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

Solving the Hicksian Problem - The utility maximization problem under budget constraint and multiple linear constraints (1) is difficult to solve directly so that, following Jackson (1991), we first focus on its Hicksian counterpart. 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 maximum levels of the constraints. We then introduce 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: $\tilde{h}_i(p,U,A,r) = h_i(\tilde{p},U)$. As shown in Jackson (1991) and Irz et al. (2015), those shadow prices are solutions of the following non-linear system:

$$\tilde{p}_i = p_i - \sum_{n=1}^{N} \mu_n a_{ni} \qquad i = 1,\ldots, H$$
$$\sum_{i=1}^{H} a_i^n h_i(\tilde{P},U) = r_n \qquad n = 1,\ldots, N < H \qquad \text{(2a \& 2b)}$$

where $\mu \geq 0$ is the *N*-vector of Lagrange multipliers associated with the *N* dietary constraints in the expenditure minimization problem. The first set of equations (2a) is easily interpreted: each shadow price is the sum of the actual price and a sum of terms depending on the nutritional/environmental coefficients of each food, as well as the influence of each constraint on minimum expenditure as measured by the Lagrange multipliers. In general, system (2) is highly non-linear and cannot be solved analytically, but we circumvent that problem by deriving relevant static comparative results describing, at the margin, the relationship between food demand and changes in dietary constraints. For a single constraint, variations in shadow prices and Hicksian demands resulting from a marginal change in the constraint r_1 are:

$$\frac{\partial \tilde{p}_k}{\partial r_1} = \frac{a_k^1}{\sum_{i=1}^{H}\sum_{j=1}^{H} s_{ij} a_i^1 a_j^1} \qquad k = 1,....H \tag{3}$$

$$\frac{\partial \tilde{h}_k}{\partial r_1} = \frac{\sum_{i=1}^{H} s_{ki} a_i^1}{\sum_{i=1}^{H}\sum_{j=1}^{H} s_{ij} a_i^1 a_j^1} \qquad k = 1,....H \tag{4}$$

where s_{ij} denotes a Slutsky coefficient $\partial h_i / \partial p_j$. Expressions (3) and (4) fully characterize the dietary adjustments as a function of two sets of parameters: the Slutsky matrix *S* describing consumer preferences and the technical coefficients a_{ij} expressing the nutritional and environmental properties of each food. Given that *S* is typically estimated empirically from observations on actual purchase behaviours, we claim that the model is therefore 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") or implicitly (through the choice of an arbitrary objective function).

Expressions (3) and (4) show that a change in a nutritional constraint 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., one Slutsky term s_{ki} differs from zero). Further, the model indicates that the magnitude and sign of any change in demand is unknown *a-priori.*

From Hicksian solution to Marshallian solution - The Hicksian problem is a useful theoretical construct but real-world consumers operate under a budget constraint rather than a utility constraint, and simulating the effects of dietary recommendations therefore requires calculation of a Marshallian solution. We first calculate the short-run private welfare cost[1] of satisfying the constraints as measured by the compensating variation *CV,* which is the difference between initial expenditure and expenditure that maintains utility constant in the nutritionally-constrained problem[2]. The compensating variation is thus also a measure of the taste cost of the constraints. Irz et al. (2015) relate the *CV* to the change in the constraint level :

$$CV = -\sum_{i=1}^{H} p_i \frac{\partial \tilde{h}_i}{\partial r_1} \tag{5}$$

[1] This welfare measure is "short-run" because it ignores the long-run health effects, and it is "private" because it ignores the external environmental cost. Those effects are taken into account in the empirical analysis, in which we calculate the cost-effectiveness of the recommendations.

[2] Note that in the constrained problem, final expenditure is evaluated at market prices (as prices do not change).

Since the constrained solutions h belong to the choice set of the unconstrained problems, $p.h \geq p.h$, and the *CV* is always negative. Its absolute value measures the level of the compensation that would make the consumer indifferent between the original diet and the diet satisfying the constraint. It follows that an approximate solution to the change in Marshallian demand Δx can be calculated from the change in Hicksian demand Δh and the income effect associated with the removal of the compensation:

$$\Delta x - \Delta h = \tilde{h}.\varepsilon^{R} \frac{CV}{p.\tilde{h}} \quad (6)$$

In this expression, ε^{R} denotes the vector of income (or expenditure) elasticities , while the ratio $CV / p.\tilde{h}$ measures the negative percentage change in the food budget corresponding to the removal of the compensation. All the other terms are either observed or calculated from equations (4) and (5).

3. The Empirical model

The behavioural model of the previous section is applied to estimate the variation in household consumption induced by the adoption of dietary recommendations for different representative households of the French population. In a second step, this variation in household consumption is translated into changes in individual food and nutrient intakes. The health effects are then assessed by using the epidemiologic DIETRON model, which permits estimation of the changes in mortality attributable to a change in diet in a given population. On the environmental side, changes in diets are converted into changes in environmental indicators using appropriate LCA-based technical coefficients. Finally, the effects of the recommendations on health, private welfare, and the environment are brought together in the analysis of the relative cost-effectiveness of the recommendations. As the model calibration was presented in detail in Irz et al. (2015), we summarize below the empirical procedure concisely, insisting on the new elements of the analysis related to the choice of constraints, the introduction of environmental constraints, and the welfare assessment integrating environmental externalities.

Choice of Recommendations - The choice of dietary constraints to be analysed is based on commonly formulated recommendations justified on health and/or environmental grounds, as well as previous analyses of the sustainability properties of diets. We first select three healthy diet recommendations because of their well-established potential to improve public health:

- Promotion of F&V has been actively pursued in many countries through social marketing campaigns of the "five-a-day" type (Capacci and Mazzocchi, 2011; Silva et al., 2013).
- Reduction in salt intake is a common aim of public health nutrition campaigns (Shankar et al., 2013).
- Reduction in SFA intake remains at the core of most healthy diet recommendations (WHO, 2003).

On the environmental side, the climate change issue currently dominates the debate about food consumption (Macdiarmid et al., 2012) and we therefore select a constraint on the CO_2e equivalent of the diet, which is a summary measure describing how much global warming can be expected from consumption of that diet. Translating a reduction in GHGEs into food-based recommendations usually results in prescriptions to reduce consumption of meat, mainly from ruminants. We therefore consider two related scenarios in the empirical analysis, namely, all meat and red meat.

***Initial diet and behavioural parameters* -** The behavioural model is calibrated using KANTAR Worldpanel data from a panel of 19,000 representative consumers of the French population. Food consumption is aggregated into 22 categories, which are defined on pages 2-3 of the supplementary material of Allais et al. (2010) and are largely self-explanatory. The price and expenditure elasticities of demand for those 22 aggregates are also drawn from Allais et al. (2010)[3] for four representative types of households differentiated according to income quartiles and henceforth referred to as "Modest", "Lower average", "Upper average", and "Well-off".

***Technical coefficients of the food aggregates and simulation procedure for the behavioural model* -** The nutrient contents of the 22 food aggregates, which are needed to formulate some constraints and simulate health effects, are calculated by combining the food composition database and average adult intakes of the component foods of each aggregate from the French dietary intake survey INCA2[4]. They have already been published as Table A.1 in Irz et al. (2015). On the environmental side, an environmental consulting firm, Greenext Service, assigned per unit values to 391 foods for two indicators: GHGEs expressed in grams of CO_2e, and air acidification in grams of sulphur dioxide equivalent (SO_2e). The two indicators were assessed by LCA (ISO, 2006a and 2006b). Thus, the environmental indicators include the impacts of each stage of the production, transformation, packaging, distribution, use, and end-of-life of food products. The final values for the two indicators reflect the average food product consumed in the French market (Greenext, 2012).

We then simulate the impact of a marginal change in the level of a dietary constraint on Marshallian demands by applying an iterative procedure based on equations (4) to (6)[5].

***Health and environmental impacts* -** To simulate the health effects, changes in food consumption at household level, as described by the behavioural model, are translated into changes in individual intakes, distinguishing between males and females[6]. This is accomplished under the assumption that (i) the percentage changes in intakes are the same for all household members, and (ii) the percentage changes are the same for at-home and out-of-home consumption[7], and using the INCA2 dietary intake database. Changes in food intakes are converted into changes in nutrients using the nutritional coefficients of the 22 aggregates, and those are then translated into changes in mortality due to diet-related chronic diseases by using the DIETRON epidemiological model of Scarborough et al. (2012)[8].

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. 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 baseline numbers of

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[3] See http://ajae.oxfordjournals.org/content/suppl/2010/01/23/aap004.DC1/aap004supp.pdf. The price elasticities for the four income groups are reported in Tables 7-10 of that document and the expenditure elasticities in Table 6.

[4] INCA2 stands for "Étude Individuelle Nationale des Consommations Alimentaires 2006-7".

[5] The need for iterations stems from the fact that the constraint is imposed in the Hicksian framework. Technical details of this are presented in Irz et al. (2015, pp. 193, section 3.5).

[6] Hence, the health model considers 8 types of individuals (i.e. 4 income groups * 2 genders).

[7] The dietary intake database covers all the foods consumed by an individual whereas the Kantar database only covers at-home consumption.

[8] More precisely, the dietary input data for the health model are intakes of: total energy (MJ/day); fruit (g/day); vegetables (g/day); fibers (g/day); total fat (% total energy); mono unsaturated fatty acids (% total energy); polyunsaturated fatty acids (% total energy); saturated fatty acids (% total energy); dietary cholesterol (% total energy); salt (g/day) (Scarborough et al., 2012).

deaths according to each disease and each income class are published in Table 3 of Irz et al. (2015), which shows that the diseases considered in DIETRON account for slightly more than one third of total French mortality.

The environmental indicators are calculated by applying the previously mentioned constant LCA-based coefficients for each food to dietary intakes. The results are presented in Table 1 for the initial (observed) average French diet across different gender and income groups. The calculated levels of CO_2e are consistent with the population average of 4092g/day reported by Vieux et al. (2012). For both pollutants and each income group, men are responsible for more emissions than women, which we explain by their larger energy intakes. There is a slight socio-economic gradient for GHGEs, with a positive association with income, which is not observed for SO_2e.

	Men				Women			
	Modest	Lower average	Upper average	Well-off	Modest	Lower average	Upper average	Well-off
DIETRON nutritional factors								
Fruits (g)	150	172	215	231	156	175	226	226
Vegetables (g)	169	193	200	193	170	182	196	186
Fibers (g)	18.4	19.1	19.8	20.7	15.1	15.6	17.1	16.9
Total Fat (% energy)	35.5	36.2	35.4	35.0	37.8	38.3	38.7	37.4
MUFA (% energy)	12.2	12.6	12.5	12.5	12.9	13.4	13.8	13.9
PUFA (% energy)	5.3	5.2	5.3	4.9	5.9	5.8	6.1	5.3
SFA (% energy)	13.8	14.3	13.6	13.5	14.8	14.9	14.5	14.1
Cholesterol (% energy)	0.14	0.14	0.13	0.14	0.14	0.14	0.14	0.14
Salt (g)	8.9	8.7	8.8	8.9	6.4	6.5	6.5	6.4
Energy (MJ)	10.2	10.4	10.5	10.7	7.7	7.8	7.9	7.8
Environmental indicators								
eq. CO2 (g)	4552	4700	4700	4773	3492	3572	3671	3739
eq. SO2 (g)	60.1	60.7	58.0	60.6	43.5	44.4	44.5	44.8

Table 1: Nutritional and environmental indicators of average daily dietary intakes, by gender and income group

Cost-effectiveness analysis - Our model calculates the effects of dietary adjustments under an "as if" assumption, i.e. assuming that the consumer complies with the 5% change in the constraint level. In practice, however, behavioural change requires public investment in social marketing campaigns and other types of interventions, with uncertain effectiveness. For this reason, our welfare assessment of alternative recommendations shies away from attempting to measure the cost of ensuring compliance with a given recommendation, but instead investigates a different question: what is the maximum amount that could be invested to promote a given recommendation so that the outcome would remain socially desirable?

Promotion of a given set of recommendations generates health benefits B_h and environmental benefits B_e, as well as costs both to individuals (i.e., the taste cost $-CV$) and the public sector (i.e, cost of interventions

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 various recommendations.

The health benefit is quantified by applying a monetary value to the reduced mortality figures calculated by DIETRON. The value of a statistical life (VSL), 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, has been reviewed elsewhere (Treich, 2015), and its estimates vary substantially across countries and policy domains. In the transportation area, the VSL reported by Anderson et al. (2011) range from 1.8 million USD 2005 for New-Zealand to 3.3 million USD 2005 for the United States, with the three represented EU countries using values in the order of 2 million USD 2005. Alternatively, Irz et al. (2015) monetise lives saved on the basis of the cost threshold of a Quality Adjusted Life Year (QALY) that is applied in the UK to investigate the cost-effectiveness of medical care. Given the average number of years of life saved for a death avoided (DA) in DIETRON, this gives a value ranging from €240k to €360k. Given the continuing debate related to the correct value of a statistical life (Doucouliagos et al., 2012), as well as widely varying values of a QALY used by different government departments in a given country[9], our baseline cost-effectiveness analysis relies on the most conservative assumption (€240/DA). The benefit estimates and cost-effectiveness threshold derived with this value should therefore be interpreted as absolute lower bounds. However, we complete the analysis by estimating benefits using the value of a death avoided more compatible with the VSL commonly used in decision making in the transport sector, namely €1 million.

On the environmental side, valuing the benefit of reduced externalities presents its own set of challenges. Regarding climate change, the European Union has initiated the world's largest carbon market, the Emission Trading Scheme (ETS), but it is widely regarded as dysfunctional (Stratham, 2013). The carbon price on that market peaked at €30/ton in 2008 but has shrunk as low as €4/ton in recent years, with this low price reflecting political failure and associated over-allocation of permits rather than the real value of carbon (Drew, 2009). In addition, some of the values used in policy assessment may ignore the biggest risks associated with climate change, and downplay the impact of current emissions on future generations (Ackerman and Stanton, 2012). In the face of so much uncertainty, we rely on a meta-analysis of the social cost of carbon developed (Tol, 2012). That author, after fitting a distribution of 232 published estimates, derives a median of €32/ton, a value which we adopt in our baseline analysis due to its rigour and objectivity. However, our sensitivity analysis also uses the value of the 95-percentile of the distribution fitted by Tol (2012), which is equal to €185/t[10].

In the case of SO_2, there is no market for emissions within the EU and the literature measuring shadow prices is dominated by US studies (Dang and Mourougane, 2014). One of the most rigorous and recent studies for the US is Mekaroonreung and Johnson (2012), who show how shadow prices depend on the choice of estimation method, and conclude to the superiority of non-deterministic methods on the basis of the compatibility of the estimated shadow prices with observed market prices. The preferred method results in shadow prices lying between 201 and 343$/ton, which translates into a range of 176 to 300€/ton. We use the mid-point of this bracket (€238/t) in our welfare assessment.

[9] Wolff and Orr (2009, p. 10) report for the UK QALY values ranging from £30k to £80k across government departments.

[10] We note that this high value is of the same order of magnitude as the highest tax currently implemented in the world (namely, 168USD/t in Sweden, which is equivalent to €148/t – see World Bank's background notes on the carbon tax available online at: http://www.worldbank.org/content/dam/Worldbank/document/SDN/background-note_carbon-tax.pdf).

4. Results

The methodology is applied to simulate the effect on food consumption, nutrient intake, health, environment, short-run welfare and cost effectiveness of six different dietary constraints. In each case, the relative variation in the level of the constraint is five percent of its baseline level, and the direction is chosen so as to increase dietary quality or lower the environmental footprint of food consumption.

Dietary adjustments and shadow prices

Table 2 displays the impact of the different recommendations on food consumption, focusing on the "lower average" income group of households. The main results reported below are not dependent on that choice, and the corresponding results for the other three household types are presented in Appendix A, Tables A.1-A.3. Each column of Table 2 corresponds to a different constraint and presents two sets of percentages: the baseline contribution of each food group to the constrained quantity (i.e., food/nutrient/CO_2e) on the left, and the change in consumption resulting from the imposition of the constraint on the right.

In general terms, it turns out that, given the relations of complementarity and substitutability among foods captured by the model, a small variation in constraint level results in relatively important changes in consumption, and substitutions between and within several food aggregates. For instance, the 'all meats' constraint (that is a five percent decrease in meat consumption corresponding to a daily consumption decrease of about 8 g/day) leads to a decrease in consumption of starchy foods (-2.2%) whereas consumption of dairy products increases (+3.4%).[11] Within the F&V group, the all meat constraint induces an increase in consumption of fresh and dry fruits whereas consumption of other products (processed fruits, F&V juices, and vegetables) decreases. Among animal products, fish consumption increases (7.5%), which could be expected, but more surprisingly egg consumption (-3.3%) decreases. Consumption of the different categories of dairy products also increases.

The magnitude of the changes and their distribution among the food groups depend on the constraint. Compared to the simulated effect described above with regard to the all meat constraint, imposition of the constraint on red meat results in smaller adjustments in food consumption. This is understandable as this constraint is less demanding in the sense that it concerns a smaller fraction of the diet and substitution with other meats occurs leading to a small decrease in 'all meats' consumption (-0.7%). Conversely, imposing an increase in F&V consumption leads to important changes in the diet. In particular consumption of starchy products (-16%) and salt-fat products (-21%) are strongly affected.

[11] Note that the decrease in consumption of the 'all meats' category is different from 5% (the target for an increase in the total consumption of meats). This is because the ready meals category also includes some meat. Then, the change in meat consumption takes into account the changes in consumption of the meat food category as well as the changes in the consumption of the other food categories which contain some meat.

Lower average	F&V +5%		Na -5%		SFA -5%		eq. CO2 -5%		Red meat -5%		All meats -5%	
Red meat	0 %	-9.1%	1 %	1.9%	3 %	-0.3%	14 %	-36.0%	90 %	-5.5%	23 %	-8.2%
Other meats	0 %	6.2%	3 %	4.6%	4 %	14.1%	13 %	-8.7%	0 %	0.7%	39 %	-6.4%
Cooked meats	0 %	-3.3%	19 %	-2.5%	9 %	-3.7%	8 %	13.0%	0 %	0.8%	32 %	-1.3%
All meats	*0 %*	*-0.3%*	*23 %*	*1.7%*	*17 %*	*5.2%*	*35 %*	*-8.0%*	*90 %*	*-0.7%*	*94 %*	*-5.2%*
Milk products	0 %	-4.3%	7 %	3.0%	8 %	-5.5%	13 %	-7.0%	0 %	0.7%	0 %	3.3%
Cheeses, butters, fresh creams	0 %	-2.9%	15 %	-4.0%	44 %	-7.4%	10 %	5.4%	0 %	0.1%	0 %	4.2%
Dairy pdts	*0 %*	*-4.0%*	*21 %*	*1.6%*	*52 %*	*-5.9%*	*23 %*	*-4.6%*	*0 %*	*0.6%*	*0 %*	*3.4%*
Fish	0 %	9.7%	4 %	7.6%	1 %	8.7%	4 %	30.6%	0 %	1.7%	0 %	7.5%
Eggs	0 %	-7.6%	1 %	4.9%	2 %	-16.0%	2 %	-16.1%	0 %	-0.8%	0 %	-3.3%
Animal pdts	*0 %*	*-2.3%*	*29 %*	*2.1%*	*19 %*	*-2.4%*	*40 %*	*-3.8%*	*90 %*	*0.3%*	*94 %*	*1.1%*
Grains	0 %	-6.2%	13 %	-16.5%	1 %	-2.2%	2 %	-6.6%	0 %	-1.0%	0 %	-0.3%
Potatoes	0 %	-27.6%	1 %	-2.8%	1 %	2.8%	1 %	-18.1%	0 %	-0.8%	0 %	-4.5%
Starchy food	*0 %*	*-16.1%*	*15 %*	*-10.2%*	*2 %*	*0.1%*	*3 %*	*-12.0%*	*0 %*	*-0.9%*	*0 %*	*-2.2%*
Fruits - Fresh	41 %	-1.1%	0 %	0.0%	0 %	-5.0%	3 %	16.5%	0 %	1.5%	0 %	2.7%
Fruits - Processed	3 %	27.0%	0 %	2.2%	0 %	-31.0%	0 %	20.0%	0 %	0.2%	0 %	-3.2%
F&V juices	6 %	4.0%	0 %	3.8%	0 %	4.6%	2 %	-0.8%	0 %	0.8%	0 %	-0.3%
Vegetables - Fresh	33 %	9.5%	3 %	6.7%	0 %	15.8%	4 %	2.0%	0 %	-0.5%	0 %	-0.3%
Vegetables - Processed	10 %	18.4%	5 %	-2.9%	0 %	10.8%	2 %	-9.7%	0 %	0.0%	0 %	-2.7%
Fruits - Dry	0 %	-6.0%	0 %	12.0%	0 %	-5.1%	0 %	54.2%	0 %	1.4%	0 %	11.7%
F&V *	*93 %*	*5.9%*	*8 %*	*2.3%*	*1 %*	*3.7%*	*11 %*	*8.6%*	*0 %*	*0.5%*	*0 %*	*0.8%*
Ready meals	4 %	-11.7%	9 %	-7.5%	4 %	-5.7%	6 %	-13.0%	10 %	-1.1%	6 %	-3.6%
Oil, margarine, condiments	0 %	12.0%	4 %	5.3%	9 %	-2.6%	1 %	-0.9%	0 %	0.1%	0 %	-1.2%
Salt-fat products	0 %	-20.7%	7 %	-27.6%	1 %	-28.4%	1 %	18.7%	0 %	1.2%	0 %	10.3%
Sugar-fat products	3 %	2.1%	6 %	-0.7%	12 %	-5.9%	5 %	2.6%	0 %	0.1%	0 %	0.3%
Soft drinks	0 %	-18.4%	0 %	-5.9%	0 %	2.8%	1 %	28.5%	0 %	0.7%	0 %	5.3%
Water	0 %	-20.0%	1 %	1.6%	0 %	9.7%	3 %	-4.8%	0 %	1.8%	0 %	10.0%
Alcoholic beverages	0 %	12.9%	0 %	1.3%	0 %	4.8%	5 %	-1.1%	0 %	0.3%	0 %	-0.4%

* Except F&V juices

Table 2: Changes in food consumption induced by the imposition of dietary constraints (percentage on the right in each column) & baseline contribution of each food group to the constrained quantity (percentage on the left in each column) for the "Lower-average" consumer type

The constraint imposed on CO_2e leads also to large changes in the diet. Consumption of animal products is negatively affected whereas consumption of F&V and relatively energy dense foods, such as salt-fat products, rises. On the whole the consumer decreases consumption of products with a 'high' CO_2e impact and increases consumption of products with a 'low' CO_2e impact. Significant adjustments in consumption occur as a result of the imposition of the SFA constraint, which induces a reduction in consumption of dairy products and, at the same time, has differentiated impacts on the consumption of other animal products. In the case of the sodium constraint, the diet is significantly affected with a decrease in the consumption of the product categories that contribute most to salt intake (cooked meats, grains, cheeses, and salt-fat products).

Table 3 presents the percentage differences between shadow prices associated with each constraint and actual prices for the "lower average" household type. Focusing on the 'all meats' constraint, we note that the shadow prices of all the food products containing meat are larger than actual prices in order to encourage lower consumption, as expected. In the case of a constraint on red meat consumption, the difference between shadow and actual prices is much lower than in the previous case. This is because the elasticity of demand for red meat demand is larger than that for all meats. In the case of red meat, there are relatively close substitutes (the other meats) whereas it is not the case for 'all meats'. It is thus easier for the consumer to reduce consumption of red meat than consumption of all meats. In the case of the F&V constraint, the relative difference between shadow and actual prices is negative as the constraint is designed to raise consumption. Moreover, its magnitude is quite large.

For the nutrient-based or CO_2e recommendations, the shadow prices of most products differ from actual prices, simply indicating that those nutrients (or CO_2e) originate from a wide range of foods. For all these constraints, we observe that some of the differences are large (i.e., at least 20%) for several product categories, which suggests that some of the substitutions required to satisfy the constraint are relatively difficult. This is particularly the case for the CO_2e recommendation meaning that reducing the CO_2e footprint of the diet is difficult.[12]

Lower average	F&V +5%	Na -5%	SFA -5%	eq. CO2 -5%	Red meat -5%	All meats -5%
Red meat	0,0%	0,8%	5,5%	82,1%	3,8%	9,8%
Other meats	0,0%	1,2%	5,7%	61,4%	0,0%	13,3%
Cooked meats	0,0%	8,6%	10,9%	34,9%	0,0%	10,6%
Fish	0,0%	2,6%	1,4%	25,9%	0,0%	0,0%
Eggs	0,0%	5,0%	20,4%	66,0%	0,0%	0,0%
Grains	-0,4%	23,1%	3,4%	39,4%	0,0%	0,0%
Potatoes	0,0%	5,5%	19,5%	54,9%	0,0%	0,0%
Fruits - Fresh	-34,7%	0,1%	0,3%	23,6%	0,0%	0,0%
Fruits - Processed	-24,4%	0,1%	0,1%	25,5%	0,0%	0,0%
F&V juices	-16,5%	0,3%	0,4%	45,4%	0,0%	0,0%
Vegetables - Fresh	-34,0%	3,0%	1,0%	34,7%	0,0%	0,0%
Vegetables - Processed	-22,7%	9,9%	1,0%	45,1%	0,0%	0,0%
Fruits - Dry	-6,5%	0,9%	6,1%	11,0%	0,0%	0,0%
Milk products	0,0%	3,1%	10,8%	59,9%	0,0%	0,0%
Cheeses, butters, fresh creams	0,0%	6,6%	54,4%	44,6%	0,0%	0,0%
Ready meals	-3,3%	6,6%	7,1%	42,1%	0,5%	3,3%
Oil, margarine, condiments	0,0%	11,0%	64,2%	35,9%	0,0%	0,0%
Salt-fat products	0,0%	28,7%	10,8%	30,1%	0,0%	0,2%
Sugar-fat products	-1,4%	2,3%	13,9%	22,4%	0,0%	0,0%
Soft drinks	0,0%	0,5%	0,6%	25,5%	0,0%	0,0%
Water	0,0%	1,4%	0,0%	55,8%	0,0%	0,0%
Alcoholic beverages	0,0%	0,1%	0,0%	23,4%	0,0%	0,0%

Table 3: Relative difference between shadow and actual prices of each food group for each dietary constraint ("Lower-average" consumer type)

[12] At least when this reduction is interpreted as resulting from an implicit taxation scheme as implied by the methodology developed in the theory section.

Effects on health and environmental indicators

The analysis of health and environmental impacts starts by converting the consumption changes described in Table 2 into changes in nutrients and environmental indicators, as presented for the whole population in Table 4. Imposition of the constraints induces substantial adjustments in the nutritional profile of the diet, but the overall change in diet quality remains ambiguous. For instance, the F&V constraint induces desirable reductions in SFA, cholesterol, salt and energy intakes, but also an undesirable decrease in intake of fibers. Similar trade-offs in diet quality can be observed for all six constraints, which justifies pursuing the assessment of health impacts by applying DIETRON to translate those nutritional changes into unambiguous health outcomes.

DIETRON is used to aggregate the nutritional adjustments into the number of deaths avoided (DA) due to the reduced incidence of CHD, strokes, and ten different types of cancer. Four constraints are estimated to reduce by around four percent the total mortality attributable to the diseases included in the DIETRON model, which can be considered substantial given the relatively small changes that are imposed exogenously (i.e., 5% change in the constraint level). However, the two constraints on meat are relatively less effective in reducing mortality as they would save about ten times less than for the other four recommendations.

Table 4 also presents the total environmental impacts of the dietary changes by reporting variations in the indicators of global warming (CO_2e) and acidification (SO_2e) for the whole population. With the exception of the SFA recommendation, all recommendations lead to a decrease in the environmental impact of the diet, and we also note that the relative reduction in SO_2e is generally larger than that in CO_2e.[13] Hence, while our analysis reveals overall synergies between the pursuits of health and environmental goals, the results also indicate that those synergies do not occur systematically. Finally, as was the case for the nutritional impact, the magnitudes of the changes in environmental indicators vary strongly across recommendations. In particular, recommendations on red meat or 'all meats' result in relatively small changes in environmental impacts, whereas the recommendations targeting F&V and CO_2e generate larger environmental improvements.[14]

[13] The exception is the recommendation on sodium.

[14] Of course, the latter occurs by construction. The reader should note that in Table 4, the composition of the diet in terms of SFA is expressed as a percentage of energy. Hence, the total change in SFA is the percentage reported in that row plus the percentage change in energy. In the case of the SFA constraint, this gives -2.3% -2.5%=-4.8%. This figure is not exactly equal to 5% because of: 1- the approximation used to calculate the Marshallian solution described in section 2; and, 2- the conversion of consumption changes into intake changes (as explained in Section 3, "Health and environmental impacts").

	F&V +5%	Na -5%	SFA -5%	eq. CO2 -5%	Red meat -5%	All meats -5%
DIETRON nutritional factors						
Fruits (g)	1.7%	0.5%	-5.4%	14.0%	1.1%	1.8%
Vegetables (g)	7.0%	2.6%	10.8%	-2.6%	-0.5%	-1.3%
Fibers (g)	-2.3%	-5.0%	-0.2%	-0.9%	-0.2%	-0.3%
Total Fat (% energy)	1.4%	2.7%	-1.0%	1.2%	0.1%	0.1%
MUFA (% energy)	2.6%	3.6%	-0.4%	0.9%	0.1%	-0.3%
PUFA (% energy)	4.7%	3.8%	0.0%	2.8%	0.2%	-0.1%
SFA (% energy)	-0.4%	1.6%	-2.3%	1.5%	0.1%	0.9%
Cholesterol (% energy)	-0.8%	3.7%	-1.5%	-2.0%	-0.1%	-1.0%
Salt (g)	-5.1%	-7.7%	-3.9%	-0.9%	-0.2%	0.3%
Energy (MJ)	-2.3%	-3.8%	-2.5%	-1.8%	-0.2%	-0.3%
% DA for DIETRON diseases	3.8%	4.2%	3.2%	3.5%	0.3%	0.4%
Environmental indicators						
eq. CO2 (g)	-2.8%	-0.8%	0.5%	-5.3%	-0.5%	-0.9%
eq. SO2 (g)	-3.9%	-0.6%	-0.4%	-9.5%	-1.0%	-2.5%

Table 4: Population average variations in nutritional and environmental indicators and in death avoided

Impacts on short-run welfare

The short-run welfare cost of satisfying the different constraints are measured by the absolute values of the compensating variations reported in the upper part of Table 5. The short-run welfare cost of satisfying the red meat constraint is the lowest (10 M€) whereas the largest is associated with the CO_2e constraint (961 M€) followed by the constraint on F&V (466 M€). In relative terms the short-run welfare costs are modest, the cost of the CO_2e constraint representing, for instance, only about 1.2% of the food budget. In most other cases, the relative welfare cost is smaller than half a percent of the food budget, and it is an almost negligible percentage for the constraints imposed on red meat and 'all meats'. However, before concluding to the insignificance of taste costs, one should keep in mind that the 5% variations in the levels of the constraints are also small. Further, the relative magnitudes of the CVs match the levels of dietary adjustments described in Table 2 and the differences between shadow and actual prices described in Table 3. Hence, the relatively large CV for the CO_2e constraint is associated with large consumption changes and large differences between actual and shadow prices, while the opposite is true for the constraint imposed on red meat. Those CVs, which capture the taste cost of healthier or more environmentally friendly diets, have to be weighed against the associated health and environmental effects for a full assessment.

	F&V +5%	Na -5%	SFA -5%	eq. CO2 -5%	Red meat -5%	All meats -5%
Consumers Cost (M€)	466	128	288	961	10	76
% food budget	0.64%	0.17%	0.37%	1.25%	0.01%	0.10%
DA	2 513	2 777	2 129	2 328	226	238
Consumers Cost per DA (K€)	185	46	136	413	46	320
Δ eq. CO2 (Kt)	-1 564	-460	260	-2 980	-275	-512
Consumers Cost to decrease eq. CO2 (€/t)	298	279		323	38	149
Δ eq. SO2 (Kt)	-27	-4	-3	-67	-7	-17
Consumers Cost to decrease eq. SO2 (€/t)	17 187	32 477	107 083	14 374	1 441	4 390

Table 5: Comparison of the constraints in terms of consumers cost, effects on health and the environment, and partial efficiency

Overall benefits and cost-effectiveness of the recommendations

To compare the efficiency of the alternative recommendations, our analysis proceeds in two steps. First, we define partial indicators of efficiency, which balance the consumer cost against the health or environmental impact as measured by a single indicator (Table 5). In a second step we present in Table 6 the global cost-effectiveness measure explained in section 3.

The consumer cost per DA varies from €46k for red meat and sodium recommendations to €413 k for the CO_2e recommendation. Those results indicate that the (partial) cost-effectiveness of the recommendations varies enormously, and that the most effective recommendations are not necessarily those that save the most lives. In the case of red meat, the high level of partial cost-effectiveness is attributable to the particularly small taste cost of the recommendation. The constraint on salt achieves the same level of partial cost-effectiveness but this is the result of both a significantly larger short-run welfare cost and a larger impact on health. By contrast, on the basis of this partial analysis, promoting a recommendation to reduce GHGEs from food consumption is a very cost-ineffective way of reducing diet-related mortality. However, we also note that for all recommendations the cost per DA compares favourably with the VSL typically used in the evaluation of transportation projects (i.e., in excess of €1million).

Turning to environmental impacts, the consumer cost per ton of CO_2e avoided varies from €38 (red meat) to more than €300 (CO_2e), except in the case of the recommendation targeting SFA, which has a negative environmental impact. When compared to the baseline estimate of the social cost of carbon (32 €/t), only the recommendation on red meat appears to approach partial cost-effectiveness, although that recommendation results in a small absolute reduction in GHGEs. Even considering the high value for the price of carbon (€185/t), the partial cost effectiveness of reducing GHGEs by promoting dietary recommendations appears poor except for the recommendations targeting meat consumption. The results for SO_2 are even worse in terms of partial cost effectiveness: reducing SO_2e by one ton through dietary adjustment imposes a consumer cost varying from €1441 for the red meat constraint to more than €30000 for the salt constraint and even more than €100000 for the SFA constraint. Those values exceed all reasonable estimates of the social cost of SO_2 emissions.

Valuation Parameters									
DA (K€/DA)	240	240	1000	1000		240	240	1000	1000
eq. CO2 (€/t)	32	185	32	185		32	185	32	185
eq. SO2 (€/t)	238	238	238	238		238	238	238	238
Constraints	Benefits (M€)				Cost (M€)	C_p Max Campaign (M€)			
F&V +5%	660	899	2 570	2 809	466	193	433	2 103	2 343
Na -5%	682	752	2 793	2 863	128	554	624	2 664	2 735
SFA -5%	503	463	2 121	2 081	288	215	175	1 832	1 793
eq. CO2 -5%	670	1 126	2 439	2 895	961	-291	165	1 478	1 934
Red meat -5%	65	107	237	279	10	54	96	226	268
All meats -5%	78	156	259	337	76	1	80	183	261

Table 6: Cost-effectiveness analysis

A complete assessment of the cost-effectiveness of the various recommendations requires that the multiple benefits and costs of each measure be considered jointly. Those population-level benefits, private costs, as well as the cost-effectiveness threshold C_p that could be allocated to promote each recommendation while ensuring overall cost-effectiveness, are presented in Table 6. Given the difficulties in valuing health and environmental improvements discussed in section 3, the calculations are repeated in separate columns for different sets of parameters defined in the upper part of the table. For the lower bound of the value of a DA (€240k) and lower value of carbon (€32/t), the first column of results shows that it would be desirable to spend considerable annual amounts of resources to promote the recommendations targeting F&V (€193 million), salt (€554 million), SFA (€215 million) and red meat (€54 million) but not those targeting GHGEs and consumption of all meats. For the first four of those recommendations, we note that C_p vastly exceeds the typical cost of running a social marketing campaign to promote dietary change. For instance, with regard to healthy eating, the ex-post evaluation of Capacci and Mazzocchi (2011) found an 8% increase in F&V consumption following a three-year "five-a-day" campaign in the UK at a cost of less than £3 million (roughly €4million). Hence, even using extremely conservative parameters to value health benefits, and taking into account the taste cost of dietary adjustment typically ignored in public health analysis, our analysis indicates that the F&V, SFA, salt and red meat recommendations are likely to be highly cost-effective. If the benefit per DA is calculated from a value closer to the VSL (€1 million), or if we use a high price of carbon (€185/t), all six recommendations appear highly cost effective. Thus, in spite of the uncertainties surrounding the valuation of non-markets goods/bads, the analysis points to the social desirability of allocating more public resources to the promotion of sustainable diet recommendations.

Table 6 can also support decision making by establishing a ranking of the recommendations to be promoted. For all scenarios, the recommendation targeting salt achieves the highest level of cost effectiveness, followed by the F&V or SFA recommendation, depending on the choice of valuation parameters. Hence, the three recommendations justified mainly on health grounds are more efficient than those with purely environmental (e.g., CO_2e) or mixed (e.g., red meat, all meats) objectives. This result is investigated further in table 7, which presents the breakdown of the total benefit into its health and environmental components. With the exception of the "all meat" recommendation monetized using the low value of a DA (€240k) and high value of CO2 (€185/t), the health benefit from adjustments in the diet always exceeds the environmental benefit.

Valuation Parameters				
DA (K€/DA)	240	240	1000	1000
eq. CO2 (€/t)	32	185	32	185
eq. SO2 (€/t)	238	238	238	238
Constraints	Share of health benefit in total benefit			
F&V +5%	91%	67%	98%	89%
Na -5%	98%	89%	99%	97%
SFA -5%	102%	110%	100%	102%
eq. CO2 -5%	83%	50%	95%	80%
Red meat -5%	84%	51%	96%	81%
All meats -5%	74%	37%	92%	71%

Table 7: Shares of total benefit attributable to health versus environmental improvements

5. Conclusion

Ex-ante assessment of informational measures urging individuals to modify their food choices for health or environmental reasons requires a clear understanding of how whole diets might respond to these policies as foods are interrelated via complex relationships of substitutability and complementarity. We address this issue by proposing a whole-diet model to analyze changes in food choice when consumers are urged to comply with dietary recommendations. This economic model, grounded in the theory of the consumer under rationing, is used empirically to estimate how the adjustments in one part of the diet, due to the adoption of such dietary recommendations, have potential consequences on the whole diet, and finally on health and environmental indicators.

This empirical analysis of dietary recommendations contributes to the existing literature on the sustainability of diets and potential convergence of solutions to food-related health and environmental issues. However, in comparison with existing approaches, our analysis takes a new step by explicitly taking into account consumers' preferences in the assessment of the effects of dietary recommendations. Indeed, unlike many other studies, the substitutions within the diet induced by the adoption of recommendations are endogenously defined on the basis of consumers' preferences characterised by price and expenditure elasticities.

The first contribution of this method is that it permits to calculate the 'taste' cost incurred by consumers, that is, the loss of utility associated with the adoption of a dietary recommendation and hence the difficulty experienced by consumers to substitute goods for one another. This feature is essential to understand the full effect of sustainable diet recommendations on consumer welfare, health and the environment and hence bring some degree of realism to the analysis of sustainable diets. The second contribution of our approach is to convert the changes in diets into health and environmental benefits. Thus, using an epidemiological model and a dataset of environmental impacts of foods, it is possible to link the dietary changes simulated by the economic model to impacts on climate change, acidification, and premature mortality from diet-related chronic diseases. The third contribution is to provide a framework for carrying out the cost-effectiveness analysis of dietary recommendations. That framework weighs the taste cost incurred by consumers against the health and environmental benefits induced by adoption of the recommendations.

Our analysis also presents some limitations, some of which relate to the data used. Health parameters used in the epidemiological model, as well as GHGEs and acidification impacts of foods remain, to some extent, uncertain. Another limitation is due to the fact that we assessed the substitutions among food categories and nutrients on the basis of consumption data, but estimated diet quality changes from a database on individual intakes. At another level, we assumed that the consumer's utility was only a function of the quantities of the products consumed, hence implicitly imposing that utility and demand relationships were unaffected by health or environmental benefits. Even if we address this issue partially when valuing the health and environmental benefits gained from the policies, a more general framework linking explicitly nutritional and environmental recommendations to changes in consumers' preferences, and hence integrating other dimensions than price and quantity into the choice problem, remains to be elaborated. Despite these limitations, we have demonstrated the practicality of the approach by investigating how food consumption, economic welfare, health and environmental outcomes would respond if French consumers adopted food-based, nutrient-based or environment-based recommendations.

The results confirm the need to consider the effects of dietary recommendations on the whole diet as, in most cases, they generate changes in the consumption of many food categories in a way that is difficult to predict. Looking solely at the magnitude of the environmental and health effects, targeting a reduction in CO_2e from the diet as well as an increase in F&V consumption represent particularly attractive options for health and the environment. Even if those measures result only in modest (5%) changes in consumption of the targeted quantity (F&V, CO_2e), they are likely to (i) prevent in excess of 2100 deaths annually, and (ii) reduce GHGEs by 1500 to 2900 kt of CO_2e per year.

It is worth stressing that in most cases, the recommendations have positive impacts on both health and the environment, which confirms the possible synergies between the two domains. However, those synergies do not occur systematically, since the recommendation to decrease by 5% SFA leads to a large number of DA but an increase in the carbon footprint of the diets.

To compare the policies in terms of cost-effectiveness, we estimated the maximum amount that could be invested by public authorities to promote a given recommendation so that the outcome would remain socially desirable. Considering a range of plausible values, it turns out that: (i) informational measures focused on F&V, SFA and sodium intakes, provided that they lead to at least a 5% change in the consumption of the targeted food or nutrients, would be valuable investments, given their impacts on health and/or environmental indicators; (ii) informational measures targeting CO_2e, red meat or all meats consumption would be valuable investments only for high valuation of DAs although that result is also sensitive to the valuation of CO_2.

Besides the ranking of different types of dietary recommendations, our analysis brings additional insights for the formulation of healthy and environmentally-friendly eating policies. Hence, the large differences between shadow and actual prices that we estimated for the health-based (F&V, sodium, SFA) and CO_2e recommendations suggest that fiscal measures are unlikely to be very effective in improving dietary quality unless the tax or subsidy rates are substantial. Note however, that the gap between the shadow and actual prices is much lower for the recommendations promoting a decrease in all meats or red meat consumption. This would suggest that price policies would be more relevant in this case.

Finally, we show that the monetary values of health benefits induced by dietary recommendations are always much greater that those of environmental benefits. This suggests prioritizing health rather than environmental issues in information campaigns dealing with food consumption.

We conclude with a broad policy message. In recent years, the consensus about effective ways of promoting healthier and more sustainable diets has shifted, with increasing pessimism towards traditional informational measures, i.e. the formulation of dietary recommendations and their promotion via social marketing campaigns, labelling regulation and/or educational measures. Hence, Traill (2012) in his presidential address on the economics of nutrition policy evaluation concluded that “Evidence suggests that information measures [...] do not much change diets”. This pessimism contrasts not only with the results of our analysis, but also the broader evidence that, at least on the health side, diet quality has in fact improved in most industrialised countries (Mazzocchi et al., 2008), even in a country such as the United States which is at the forefront of the “obesity epidemic” (Beatty et al., 2014). Further, when looking at broad trends over a long period of time, there is evidence of very large changes in dietary habits that, at least in some countries, are explained in part by the effect of public interventions.[15] While recognising the difficulty of identifying the causal determinants of those trends (e.g., price and income changes versus health considerations), what might be needed is: 1- A revision of expectations regarding the effect of a short term intervention. Our analysis suggests that even a minute change in food consumption patterns can ensure cost effectiveness of a policy; and 2- A more sustained effort in promoting sustainable diet recommendations. At that level, the analysis indicates that public expenditures in the tens or hundreds of millions of Euros per year – levels that are dwarfed by expenditure on food and drinks advertising by private businesses (Matthews, 2007) - may be justified on efficiency grounds.

Conflicts of interest

The authors do not have any actual or potential conflict of interest to declare.

Acknowledgments

We wish to thank Olivier Allais for providing some of the dataand parameters upon which the empirical model is based. Thisresearch is an output of the following projects: OCAD, funded bythe French ANR (ANR 11 ALID 002 03); FOODPOL, funded by INRAmetaprogram DID’IT; VASTUUFOORUMI, funded by MTT’s strategicprogram VARU; and ERA-Net SUSFOOD SUSDIET (Grant agreementno. 291766), with the Daniel and Nina Carasso Foundation andMMM-MAKERA as national funders for the French and Finnish part-ners respectively.

[15] See for instance Prättälä’s presentation of the collapse in the use of butter as spread and concurrent surge in consumption of margarine and vegetables in Finland from 1978 to 2002 (Prättälä, 2003, Figure 1).

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Appendix A:

Modest	F&V +5%		Na -5%		SFA -5%		eq. CO2 -5%		Red meat -5%		All meats -5%	
Red meat	0%	-17.3%	1%	1.9%	3%	-0.4%	13%	-38.4%	88%	-5.6%	21%	-8.6%
Other meats	0%	13.0%	2%	4.9%	4%	14.5%	12%	-8.7%	0%	0.7%	38%	-6.4%
Cooked meats	0%	-6.5%	18%	-2.2%	8%	-3.1%	8%	13.4%	0%	0.8%	34%	-1.4%
All meats	*0%*	*-0.1%*	*22%*	*1.8%*	*15%*	*5.4%*	*33%*	*-7.7%*	*88%*	*-0.6%*	*93%*	*-5.2%*
Milk products	0%	-8.1%	7%	2.9%	9%	-4.4%	14%	-8.0%	0%	0.6%	0%	3.1%
Cheeses, butters, fresh creams	0%	-5.5%	15%	-3.7%	43%	-7.4%	10%	5.3%	0%	0.1%	0%	4.1%
Dairy pdts	*0%*	*-7.6%*	*21%*	*1.7%*	*52%*	*-5.0%*	*24%*	*-5.5%*	*0%*	*0.5%*	*0%*	*3.3%*
Fish	0%	24.0%	3%	8.4%	1%	8.7%	3%	34.2%	0%	1.7%	0%	7.9%
Eggs	0%	-14.2%	1%	4.9%	2%	-14.8%	2%	-16.9%	0%	-0.8%	0%	-3.3%
Animal pdts	*0%*	*-4.3%*	*27%*	*2.2%*	*18%*	*-2.0%*	*38%*	*-4.4%*	*88%*	*0.2%*	*93%*	*1.2%*
Grains	0%	-11.1%	15%	-16.1%	1%	-0.6%	3%	-6.2%	0%	-0.8%	0%	0.0%
Potatoes	0%	-46.7%	1%	-2.6%	1%	3.3%	1%	-18.9%	0%	-0.8%	0%	-4.7%
Starchy food	*0%*	*-26.8%*	*16%*	*-10.1%*	*2%*	*1.1%*	*4%*	*-11.8%*	*0%*	*-0.8%*	*0%*	*-2.1%*
Fruits - Fresh	40%	-6.8%	0%	0.0%	0%	-5.3%	3%	17.4%	0%	1.5%	0%	2.6%
Fruits - Processed	3%	51.2%	0%	2.4%	0%	-29.0%	0%	20.5%	0%	0.1%	0%	-3.3%
F&V juices	7%	4.6%	0%	4.0%	0%	4.7%	2%	-0.9%	0%	0.8%	0%	-0.4%
Vegetables - Fresh	31%	10.6%	3%	7.7%	0%	16.3%	3%	2.0%	0%	-0.6%	0%	-0.9%
Vegetables - Processed	11%	33.1%	5%	-3.0%	0%	10.6%	2%	-9.7%	0%	0.0%	0%	-2.3%
Fruits - Dry	0%	-12.0%	0%	12.4%	0%	-4.6%	0%	58.9%	0%	1.4%	0%	12.0%
F&V *	*92%*	*6.4%*	*8%*	*2.5%*	*1%*	*3.8%*	*11%*	*8.7%*	*0%*	*0.5%*	*0%*	*0.6%*
Ready meals	5%	-21.6%	10%	-7.0%	4%	-4.5%	6%	-13.0%	12%	-1.0%	7%	-3.6%
Oil, margarine, condiments	0%	19.4%	4%	4.2%	9%	-5.6%	2%	-0.7%	0%	0.1%	0%	-0.9%
Salt-fat products	0%	-33.0%	7%	-26.5%	1%	-25.0%	1%	18.4%	0%	1.1%	0%	9.6%
Sugar-fat products	3%	2.2%	6%	-0.3%	13%	-4.9%	6%	3.8%	0%	0.1%	0%	0.5%
Soft drinks	0%	-28.0%	0%	-4.0%	0%	4.1%	1%	26.2%	0%	0.6%	0%	4.8%
Water	0%	-36.1%	1%	1.6%	0%	9.5%	3%	-4.2%	0%	1.9%	0%	11.0%
Alcoholic beverages	0%	33.4%	0%	1.1%	0%	4.2%	5%	-3.1%	0%	0.3%	0%	-1.0%

* Except F&V juices

Table A.1: Changes in food consumption induced by the imposition of dietary constraints (percentage on the right in each column) & baseline contribution of each food group to the constrained quantity (percentage on the left in each column) for the "Modest" consumer type.

Upper average	F&V +5%		Na -5%		SFA -5%		eq. CO2 -5%		Red meat -5%		All meats -5%	
Red meat	0%	-6.4%	1%	1.7%	3%	-0.9%	14%	-36.6%	89%	-5.5%	23%	-8.3%
Other meats	0%	4.0%	3%	4.5%	4%	13.7%	13%	-8.9%	0%	0.7%	39%	-6.4%
Cooked meats	0%	-2.4%	19%	-2.5%	9%	-4.3%	7%	13.2%	0%	0.8%	32%	-1.1%
All meats	*0%*	*-0.4%*	*23%*	*1.7%*	*16%*	*4.7%*	*34%*	*-8.4%*	*89%*	*-0.7%*	*93%*	*-5.2%*
Milk products	0%	-3.2%	6%	3.0%	8%	-6.4%	12%	-6.9%	0%	0.7%	0%	3.1%
Cheeses, butters, fresh creams	0%	-2.2%	15%	-4.3%	45%	-7.2%	10%	5.1%	0%	0.1%	0%	4.0%
Dairy pdts	*0%*	*-3.0%*	*21%*	*1.5%*	*53%*	*-6.6%*	*22%*	*-4.5%*	*0%*	*0.6%*	*0%*	*3.3%*
Fish	0%	4.6%	4%	6.7%	1%	8.1%	4%	27.8%	0%	1.5%	0%	6.8%
Eggs	0%	-5.4%	1%	4.8%	2%	-16.4%	2%	-16.6%	0%	-0.9%	0%	-3.5%
Animal pdts	*0%*	*-1.8%*	*29%*	*2.0%*	*19%*	*-2.8%*	*40%*	*-3.6%*	*89%*	*0.2%*	*93%*	*1.0%*
Grains	0%	-4.6%	13%	-16.9%	1%	-3.5%	2%	-7.7%	0%	-1.1%	0%	-0.7%
Potatoes	0%	-19.5%	1%	-3.0%	2%	2.4%	1%	-18.7%	0%	-0.8%	0%	-4.7%
Starchy food	*0%*	*-12.2%*	*14%*	*-9.8%*	*2%*	*-0.5%*	*3%*	*-13.3%*	*0%*	*-1.0%*	*0%*	*-2.7%*
Fruits - Fresh	42%	2.1%	0%	0.3%	0%	-3.7%	4%	15.6%	0%	1.3%	0%	2.5%
Fruits - Processed	2%	17.4%	0%	1.9%	0%	-33.0%	0%	20.0%	0%	0.1%	0%	-3.7%
F&V juices	5%	2.5%	0%	3.6%	0%	3.9%	2%	-1.2%	0%	0.8%	0%	-0.5%
Vegetables - Fresh	36%	8.3%	4%	5.7%	0%	14.0%	5%	1.7%	0%	-0.4%	0%	0.0%
Vegetables - Processed	8%	11.8%	4%	-2.9%	0%	10.2%	2%	-10.9%	0%	-0.1%	0%	-3.4%
Fruits - Dry	0%	-3.4%	0%	10.2%	0%	-3.8%	0%	48.4%	0%	1.2%	0%	9.8%
F&V *	*94%*	*5.7%*	*9%*	*2.3%*	*1%*	*3.9%*	*13%*	*8.2%*	*0%*	*0.5%*	*0%*	*0.9%*
Ready meals	4%	-8.1%	9%	-7.9%	4%	-6.4%	6%	-13.8%	10%	-1.1%	6%	-3.8%
Oil, margarine, condiments	0%	8.4%	4%	6.0%	9%	-0.4%	1%	-1.6%	0%	0.1%	0%	-1.6%
Salt-fat products	0%	-15.0%	7%	-28.1%	1%	-29.4%	1%	18.8%	0%	1.2%	0%	10.4%
Sugar-fat products	2%	1.5%	5%	-1.2%	11%	-6.6%	5%	0.9%	0%	0.1%	0%	-0.1%
Soft drinks	0%	-14.7%	0%	-8.0%	0%	0.8%	1%	32.1%	0%	0.8%	0%	5.6%
Water	0%	-13.6%	1%	1.5%	0%	9.1%	3%	-5.5%	0%	1.7%	0%	9.4%
Alcoholic beverages	0%	6.5%	0%	1.4%	0%	4.9%	6%	0.0%	0%	0.3%	0%	-0.2%

* Except F&V juices

Table A.2: Changes in food consumption induced by the imposition of dietary constraints (percentage on the right in each column) & baseline contribution of each food group to the constrained quantity (percentage on the left in each column) for the "Upper-average" consumer type.

Well-off	F&V		Na		SFA		eq. CO2		Red meat		All meats	
	+5%		-5%		-5%		-5%		-5%		-5%	
Red meat	0%	-5.4%	2%	1.5%	4%	-1.5%	14%	-36.6%	89%	-5.5%	24%	-8.7%
Other meats	0%	3.5%	3%	4.5%	4%	14.2%	12%	-8.6%	0%	0.7%	38%	-6.4%
Cooked meats	0%	-1.9%	18%	-2.5%	8%	-5.1%	7%	13.4%	0%	0.9%	30%	-0.6%
All meats	*0%*	*-0.3%*	*22%*	*1.7%*	*16%*	*4.5%*	*33%*	*-8.8%*	*89%*	*-0.7%*	*93%*	*-5.2%*
Milk products	0%	-2.6%	6%	3.0%	8%	-7.3%	11%	-6.6%	0%	0.7%	0%	3.1%
Cheeses, butters, fresh creams	0%	-2.0%	16%	-4.4%	46%	-7.4%	10%	4.7%	0%	0.1%	0%	4.0%
Dairy pdts	*0%*	*-2.5%*	*22%*	*1.4%*	*54%*	*-7.3%*	*21%*	*-4.1%*	*0%*	*0.6%*	*0%*	*3.3%*
Fish	0%	2.4%	5%	5.9%	1%	7.6%	5%	24.5%	0%	1.3%	0%	6.3%
Eggs	0%	-4.5%	1%	5.0%	2%	-17.3%	2%	-16.7%	0%	-0.9%	0%	-4.1%
Animal pdts	*0%*	*-1.6%*	*29%*	*2.0%*	*19%*	*-3.2%*	*39%*	*-3.4%*	*89%*	*0.2%*	*93%*	*1.0%*
Grains	0%	-3.9%	12%	-17.0%	1%	-4.6%	2%	-8.4%	0%	-1.2%	0%	-1.1%
Potatoes	0%	-17.0%	1%	-3.3%	1%	3.2%	1%	-19.4%	0%	-0.9%	0%	-5.7%
Starchy food	*0%*	*-10.2%*	*13%*	*-10.3%*	*2%*	*-0.8%*	*3%*	*-13.7%*	*0%*	*-1.1%*	*0%*	*-3.3%*
Fruits - Fresh	46%	4.1%	0%	0.7%	0%	-2.3%	4%	14.2%	0%	1.1%	0%	2.5%
Fruits - Processed	2%	13.2%	0%	1.7%	0%	-34.5%	0%	19.6%	0%	0.2%	0%	-4.2%
F&V juices	5%	1.9%	0%	3.5%	0%	3.4%	2%	-1.6%	0%	0.8%	0%	-0.6%
Vegetables - Fresh	35%	7.1%	5%	5.1%	1%	13.1%	5%	1.4%	0%	-0.3%	0%	0.0%
Vegetables - Processed	6%	8.7%	4%	-2.5%	0%	10.0%	2%	-11.9%	0%	-0.1%	0%	-4.6%
Fruits - Dry	1%	-2.3%	0%	8.5%	0%	-3.1%	0%	41.8%	0%	1.0%	0%	8.5%
F&V *	*94%*	*5.7%*	*9%*	*2.2%*	*1%*	*3.8%*	*13%*	*7.8%*	*0%*	*0.5%*	*0%*	*1.0%*
Ready meals	4%	-6.2%	11%	-7.7%	4%	-6.4%	6%	-13.3%	11%	-1.1%	7%	-3.9%
Oil, margarine, condiments	0%	7.4%	4%	7.4%	8%	3.8%	1%	-2.4%	0%	0.0%	0%	-2.3%
Salt-fat products	0%	-12.5%	7%	-28.3%	1%	-30.6%	1%	18.2%	0%	1.3%	0%	10.7%
Sugar-fat products	2%	1.5%	5%	-1.6%	10%	-7.4%	4%	-1.1%	0%	0.1%	0%	-0.6%
Soft drinks	0%	-14.2%	0%	-11.0%	0%	-1.8%	1%	37.7%	0%	0.9%	0%	6.5%
Water	0%	-10.8%	1%	1.3%	0%	8.5%	3%	-6.0%	0%	1.6%	0%	9.2%
Alcoholic beverages	0%	3.5%	0%	1.6%	0%	5.0%	7%	1.3%	0%	0.3%	0%	0.1%

* Except F&V juices

Table A.3: Changes in food consumption induced by the imposition of dietary constraints (percentage on the right in each column) & baseline contribution of each food group to the constrained quantity (percentage on the left in each column) for the "Well-off" consumer type.