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Co-benefits of changing diet. A modelling assessment at the regional scale integrating social acceptability, environmental and health impacts

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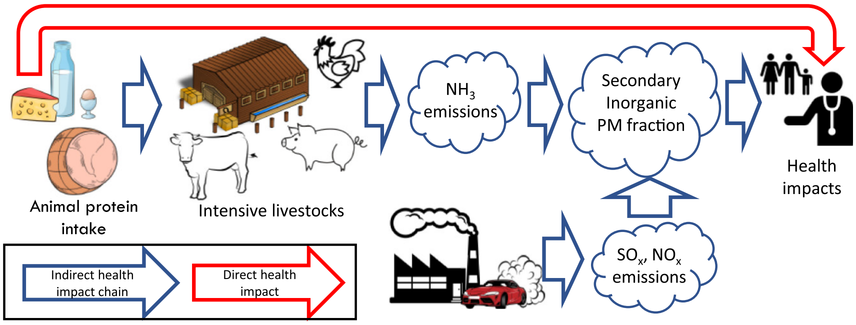
HIGHLIGHTS

- A diet rich in animal proteins can affect human health directly and indirectly.
- Lombardy region (Italy) air quality is strongly affected by the breeding industry.
- Benefits of changing dietary habits are assessed through a transdisciplinary approach.
- Radical dietary habit changes are needed to reduce ammonia emissions.
- End of pipe measures must be implemented to effectively reduce ammonia emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Several commentaries have suggested that the overconsumption of animal foods exerts several detrimental effects on human and environmental health. However, no studies have accurately estimated the impact of a reduction in animal food consumption on mortality due to the direct effects on metabolic health (i.e. animal protein and saturated fat intake as modulators of pathways leading to cardiovascular disease, cancer and accelerated ageing), and indirect effects on health due to excessive exposure to pollutants (i.e. PM_{10} concentrations originated by livestock ammonia emissions).

The proposed modelling approach is innovative since it integrates social acceptability, environmental and health impacts. It is adopted to investigate different scenarios at a regional scale presenting the Lombardy region case study. The work focuses on the impact on the human and environmental health of diets characterized by three different animal protein intake levels. Our integrated assessment modelling approach faces the issue from two points of view. On one side, it estimates the mortality due to the population exposure to PM_{10} concentrations including the inorganic fraction originated by livestock ammonia emissions, on the other, it evaluates the mortality (i.e. total, cardiovascular and cancer) due to high dietary animal protein and/or saturated fat intake. The impacts of the mentioned animal protein intake levels of diets are also estimated through the people willingness to change their eating behaviour. The importance of putting in place end-of-pipe and energy measures in order

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[1] Disclaimer: The views expressed are purely those of the author and may not in any circumstances be regarded as stating an official position of the European Commission. Since March 2017 Eva Valeri is employed at Autorità di Regolazione dei Trasporti (the Italian transport regulation authority), but this article presents the results of former research and does not represent the views of the authority.

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to reduce ammonia and methane emissions from the breeding activities, going further the current EU legislation on air quality and climate, is emphasized.

1. Introduction

Several studies have suggested that the overconsumption of animal foods exerts several detrimental effects on human and environmental health and various studies have been published that accurately estimate the impact of a reduction in animal food consumption on mortality due to the effects on metabolic health, i.e. animal protein and saturated fat intake as modulators of pathways leading to cardiovascular disease, cancer and accelerated ageing (e.g. Chen et al., 2016; Fontana and Partridge, 2015; Zong et al., 2016; Levine et al., 2014, Tosti et al., 2018).

At the same time, the intensive agri-food industry, which is triggered by the increasing demand of high-protein animal products, is the primary cause of emission of ammonia (NH_3) which, reacting with other inorganic species present in the polluted atmosphere (e.g. NOx emitted by vehicular traffic, domestic heating, energy production and industry), is responsible for the formation of the secondary inorganic fraction of the fine Particulate Matter (PM) (Hertel et al., 2011; Fuzzi et al., 2015; Viney et al., 2009). Through NH_3 emissions, the food industry, and breeding activities, in particular, is impacting the environment (Notarnicola et al., 2017) and contributing to the population exposure to the fine fraction of the atmospheric PM, which produces several detrimental effects on human health (see e.g. Brink and van Grinsven, 2011; Pope et al., 2009; Westhoek et al., 2014; Burnett et al., 2018). Also, through the emissions of enteric CH_4, breeding activities have been estimated to be responsible for about 10% of global greenhouse gas (GHG) emissions (Global Carbon Project- https://www.globalcarbonproject.org/index.htm).

Ammonia emission reduction could be effectively obtained either via end-of-pipe solutions (Bittman et al., 2014) or through lifestyle changes when e.g. people reduce their protein intake through a lower consumption of meat and dairy products, being farm animals considered the greatest contributor to anthropogenic ammonia emissions. However, while end-of-pipe technologies have an impact only on the health effects due to pollution exposure via the reduction of atmospheric PM levels, dietary changes might impact also on the metabolic health effects. In this work, it is assumed that the changes in meat and dairy consumption correspond to equivalent changes in the size of livestock production (Westhoek et al., 2015).

In this context, it is therefore important to analyse individual preferences towards environmental policies also promoting potential changes in the dietary habits, i.e. the consumer's reaction for a reduction of consumption of meat and dairy products.

The problem of devising effective policies aimed at reducing the pollutant levels and the related health impacts can be successfully tackled by using Integrated Assessment Models (IAMs). IAMs bring together data on pollutant emissions and levels as well as on human exposure, with information on potential emission reduction measures of pollutants and the closely related greenhouse gases, and their respective implementation costs) (Guariso et al., 2016; Reis et al., 2005). At the European scale, the most extensively used IAM is the RAINS (Regional Air Pollution Information and Simulation) model and its extension GAINS (Greenhouse Gas–Air Pollution Interactions and Synergies) model (Wagner et al., 2007), the latter aimed at identifying cost-effective emission control strategies that simultaneously tackle local air quality and GHGs, thus maximizing benefits (Amann et al., 2011). In many nations, GAINS has been adapted to the national scale as a tool to assess emission reduction potentials in a given country (e.g. D'Elia et al., 2009; Oxley and ApSimon, 2007; Syri et al., 2002). At the regional scale, the RIAT (Regional Integrated Assessment Tool) model has been used in various regions (Lombardy and Emilia Romagna in Italy and Alsace in France) to identify the most efficient mix of local policies required to reduce tropospheric ozone and particulate matter, taking into account local peculiarities in terms of emissions, meteorology and technological, financial and social constraints (Carnevale et al., 2012a). A recent development of IAMs at the national to urban scale is represented by the MAQ (Multi-dimensional Air Quality) model (Turrini et al., 2018) used in this study.

Previous studies have already addressed the issue of evaluating the benefits for human health and environment and/or climate of reducing the intake of animal proteins (Berners-Lee et al., 2012; Springmann et al., 2016; Tilman and Clark, 2014; Westhoek et al., 2014). Other IAM based studies have evaluated the efficacy of addressing the agri-food sector emissions to reduce PM levels (Pinder et al., 2007; Giannadaki et al., 2018). Finally, behavioural studies have dealt with the issue of how to promote a shift to a plant-based diet (Joyce et al., 2012).

In this study, for the first time, we performed an Integrated Assessment of *i*) the metabolic health impacts induced by a reduced intake of animal proteins; *ii*) the health impacts due to the reduction of secondary PM generated by the breeding industry, *iii*) the impact on GHG emissions due to a reduction in the breeding activities, and *iv*) the people willingness to change their dietary habits through stated choice experiments, in other words, the degree of social acceptability of environmental policies aimed at curbing animal protein consumption.

The study domain considered in the present study is the Lombardy region located in the Po basin in northern Italy. The Po basin is one the most polluted, urbanized and industrialised areas in Europe (EEA, 2018), where a significant number of PM_{10} (particulate matter 10 μm or less in diameter) exceedances above the limits of the European air quality directive (European Directive, 2008/50/EC) and of the World Health Organization (WHO, 2005) are recorded (EEA, 2018; Putaud et al., 2010). This implies exceedances also of the average exposure indicator (AEI) and, as a consequence, severe impacts on the population health. The huge number of intensive breeding activities insisting upon the region (55% and 35% of the Italian livestock and agricultural production, respectively) together with emissions from the industry, the transport sector and from biomass burning, combined with the region topography (Carnevale et al., 2018) are responsible for the high PM_{10} levels recorded not only in urban areas but also at rural sites.

2. Methods

In this section, we describe the modelling system designed to estimate the impacts of a reduction in animal food consumption. The system is composed of a set of models that covers the social, environmental and health aspects to assess the impact of different levels of animal protein intake, assuming that a protein intake reduction affects the extent of livestock. This, in turn, results in a reduction of PM_{10} concentration and GHG emissions.

The modelling system schematic diagram is given in Fig. 1 and it consists of:

- A direct health impact model (Section 2.1) to assess the health risk and the estimation of direct health effects in terms of premature deaths and Years of Life Lost (YLL) determined by the protein intake variation;
- A modelling chain based on the MAQ model to assess i) the reduction of NH3 emissions due to protein intake variation; ii) the resulting changes in population exposure to PM10 and related indirect health effects in terms of the same mortality indicators (YLL);

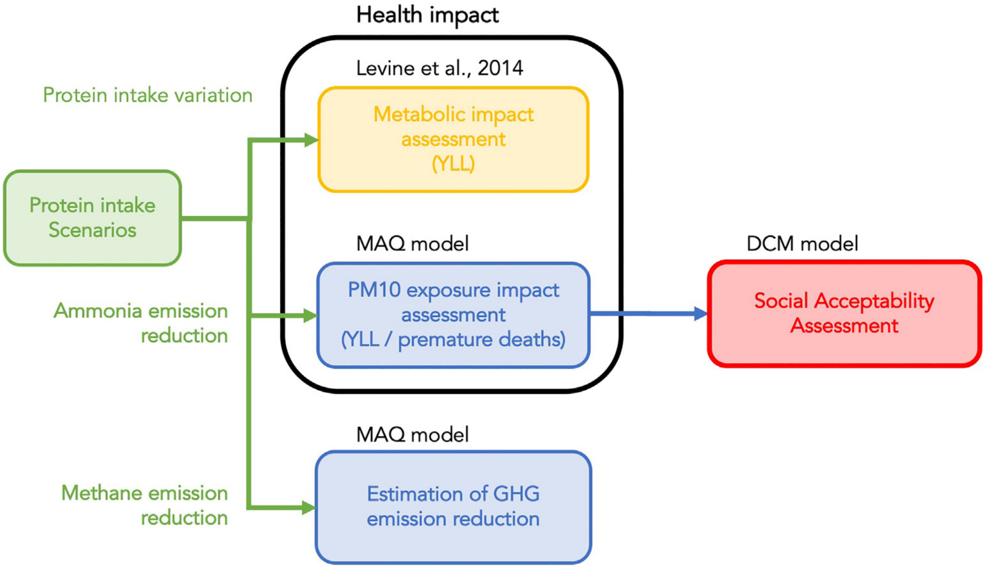

Fig. 1. Modelling system schematic diagram.

iii) changes in GHG emissions (Section 2.2).

- A DCM (Discrete Choice Model) to assess the social acceptability of selected animal protein intake scenarios proposed to population, analysing stated choice data (Section 2.3);

The metabolic health impacts have been evaluated in terms of reduced YLL according to the hazard ratio provided by Levine et al. (2014). This paper highlights that, for people between 50 and 65, an animal protein intake higher than 10% of the total daily calories can increase the all cause-mortality hazard ratio, so, scenarios have been developed considering an animal protein intake lower than 10% of the daily total calories.

The impacts on health due to a reduced PM exposure as well as the impact on GHG emission have been evaluated using the MAQ (Multi-dimensional Air Quality) model. MAQ has been developed to define cost-effective air quality plans at different scales (urban to national) and co-benefits for GHG emissions (Turrini et al., 2018). MAQ can assess the effectiveness of end-of-pipe, energy and fuel switch measures, including behavioural changes, as e.g. changes in dietary habits. MAQ integrates all the components of the DPSIR scheme (Drivers-Pressures-State-Impacts-Responses), adopted by the EU (European Environment Agency, 1999). In particular, it allows assessing policy scenarios or the solution of an optimization problem by iteratively changing the abatement measures applied (RESPONSES) that affect the human activities (DRIVERS) and directly reduce emissions (PRESSURES). This modifies air pollutant levels (STATE) resulting in the variation of IMPACTS. The impacts are then evaluated, and RESPONSES are accordingly assessed.

The socio-economic analysis is based on DCM analysis aimed at modelling the way people choose between a set of alternatives of potential environmental measures. DCMs are useful for analysing and predicting how people's choices are influenced by their personal characteristics and by the different measures' drivers. Widely used in many fields such as marketing, transportation, housing, communications, energy, health and social care, insurance, labour, agriculture and food (Ben-Akiva and Lerman, 1985; Ben-Akiva et al., 2002; Louviere et al., 2000; McFadden, 1981; Train, 2002), DCEs are based on the microeconomic approach of consumer behaviour based on the utility maximization under a budget constraint. They imply the design and implementation of a field survey including the experimental design definition, the questionnaire setting and administration, data collection and sampling strategy, the model analysis and interpretation, as well as some internal and external validity checks (Hensher et al., 2005).

2.1. Metabolic model

Based on Levine et al. (2014), we computed the reduction in YLL due to lower protein intake in the 50–65-year-old population group. For each 5-years wide population cohort *c*, the following equations have been applied:

$$YLL^c = \frac{\left(d_0^c - d_p^c\right)\cdot LE^c}{100000}$$

where LE^c is the average life expectancy for cohort c and d_0^c, d_p^c are the number of deaths for cohort c per 100,000 people in the base case (d_0^c) and in the case with low protein intake (d_p^c). These last two terms can be computed as:

$$d_p^c = s_p^c - s_p^{c+1}$$

where

$$s_p^c = s_0^{c-1} - s_0^{c-1}\left(\frac{q^{c-1}}{HR\cdot 1000}\right)$$

$$s_0^c = s_0^{c-1} - s_0^{c-1}\left(\frac{q^{c-1}}{1000}\right)$$

In the previous equations, s_0^c represents the number of survivors for the cohort c, given a crude death rate per cohort q^c. Instead, s_p^c is the number of survivors for the cohort c, given a death rate modified through the hazard ratio due to reduced protein consumption (HR). This last condition, according to the aforementioned paper, results in a 30% all-cause mortality risk increase (HR: 1.3).

2.2. The MAQ model: PM_{10} exposure and GHG emission impact assessment

Ammonia produced by breeding activities reacts with other inorganic species in the atmosphere contributing to the secondary inorganic fraction of PM. Population exposure to PM produces a broad range of effects on human health predominantly to the respiratory and cardiovascular systems (WHO, 2005).

In this work, the PM exposure-related health impacts have been evaluated through the application of the MAQ system integrating the ExternE approach (Bickel et al., 2005). This, to estimate the impact on all-cause yearly mortality due to long term PM_{10} exposure expressed in YLL.

To compute health impacts, the calculated PM_{10} concentrations are multiplied by the number of 30 to 90 years-old citizens residing in each cell of the domain and for a coefficient that determines the incidence of the pollutant on the years of lost life. The equation to compute the YLL for the morbidity indicator m is:

$$YLL = \sum_{d=1}^{D} \gamma \cdot P_d \cdot AQI_d$$

where:

- γ is the incidence of the PM_{10} concentrations exposure on the YLL and it is equal to $0.0004\,\frac{YLL \cdot m^3}{\mu g \cdot pers}$;
- P_d is the population, from 30 to 90-year-old, exposed to PM_{10} pollution in cell d;
- AQI_d indicates the mean PM_{10} concentrations, in cell d in $\frac{\mu g}{m^3}$.

MAQ also estimates the GHG emission reduction resulting from the application of the abatement measures.

2.3. Discrete choice model: social acceptability evaluation of changes in eating behaviour

Policies involving behavioural measures are likely to play an increasingly important role in future environmental and air quality management in Europe. To design effective policies behavioural and habit changes need inevitably to be taken into account, individual preferences towards the main policy drivers must be assessed. The present study is built on a stated choice experiment survey, designed and implemented in Italy in 2015 within the EU project SEFIRA (Socio-Economic Implication for Individual Responses to Air Pollution policies in EU), implying the submission to 2,400 Italian citizens of a questionnaire with a DCM exercise (Valeri et al., 2016). The sample is nationally representative reflecting the distribution of population 18+ in terms of age and gender at NUTS-3 level so that it can include both urban and rural areas. Respondents eat meat or dairy products for more than four days per month. Are therefore excluded vegetarians and vegans.

The survey was aimed at evaluating the acceptability of a set of environmental policies focussing on air quality; the exercise highlighted the role of different attributes affecting such acceptability, thus measuring the importance assigned by respondents to the personal engagement in term of changes, among the others, in the eating habits. A segmentation analysis based on socio-economic and demographic characteristics of respondents, complemented by their attitudes towards both environmental awareness and intention, allowed us to cluster respondents by different sensitivities towards changes in dietary habits.

From the aim of this study, we take into account the choice between two (out of five) potential environmental policies characterized by the following policy drivers:

- the personal engagement in terms of changes in the eating habits: defined as the required reduction in the consumption of beef, pork, lamb or dairy products, expressed in the number of days fewer per month; three attribute levels have been created pivoting, for each respondent, a reduction of 25% and 50% on the current level of consumption. The “No change” option was included;
- the reduction of premature deaths: described as the impact of the policy on the reduction of the number of premature deaths caused by atmospheric pollution, with the following attribute levels: 50,000, 150,000 and 250,000 fewer premature deaths annually.

Estimating individual preferences with a Latent Class modelling approach, we found three clusters of respondents characterized by different eating habits and environmental awareness and intentions (Valeri et al., 2016). All clusters report a significant and positive sensitivity to the improvement of the reduction of premature deaths caused by exposure to atmospheric pollutants, while the personal engagement in terms of changes in the dietary habits varies across all clusters. The estimated individual heterogeneity between the different clusters has been used here to carry out a scenario analysis.

Considering that the policy drivers (dietary habits and premature deaths) simultaneously varied across choice scenarios based on the drawn experimental design, we calculated the marginal rates of substitution between them that measures the degree to which individuals are willing to trade one attribute, in this case, policy driver, for another (Zweifel et al., 2006). This is particularly important for those individuals who perceive the dietary habits' change as negative on the overall utility (i.e. satisfaction) for a potential environmental policy. Focusing on the cluster of respondents resulting more reluctant to changes in their eating habits, through a scenario analysis we investigated the compensation required, in terms of the number of premature deaths, to accept a reduction in the animal intake habits. Then, we quantified the compensation required to achieve the goal of the tested policy scenarios, establishing a link with the reduction in the number of premature deaths estimated through the MAQ methodology.

2.4. Uncertainty assessment

The YLL estimates due to PM_{10} exposure can be affected by the modelling system uncertainties (Carnevale et al., 2016a, 2016b). The assessment of such uncertainty is appraised by computing how a variation of ±5% of breeding activities, applied to the protein intake scenarios, affects emissions, concentrations, exposure and YLL.

As it is for the social acceptability analysis, in order to identify how to compensate a specific amount of premature deaths in the Lombardy region by a behavioural change consisting of a reduction of meat and dairy products, we use the marginal rate of substitution between the two attributes (i.e. required changes in eating habits and reduction of premature deaths), that is the ratio of the two coefficient estimates. This is commonly called “willingness to pay” when a monetary coefficient is considered at the denominator. To further investigate parameter uncertainty and avoid to simply use point estimates, we calculated the confidence intervals of the marginal rate of substitution.

3. Modelling system set-up for the case study

The analysis for protein reduction scenarios is applied to Lombardy region in Northern Italy. This domain (shown in Fig. 2) has been discretized with a $6 \times 6\ km^2$ resolution for a total of 6,000 cells. The modelling setup requires the following databases:

3.1. Emission-concentration model database

Statistical surrogate models have been identified and harmonized in the MAQ system to provide the link between precursors emissions and PM_{10} concentrations. Among statistical models, the Artificial Neural Network model class has been applied (Corani, 2005; Carnevale et al., 2012b). To train the Neural Network Surrogate Models, a set of 14 scenarios has been built to include the highest information content and cover possible variations of emission precursors, spanning between a maximum value, which corresponds to the “base case” year and a minimum value corresponding to the Maximum Feasible Reduction (MFR) scenario. These training scenarios have been simulated through TCAM

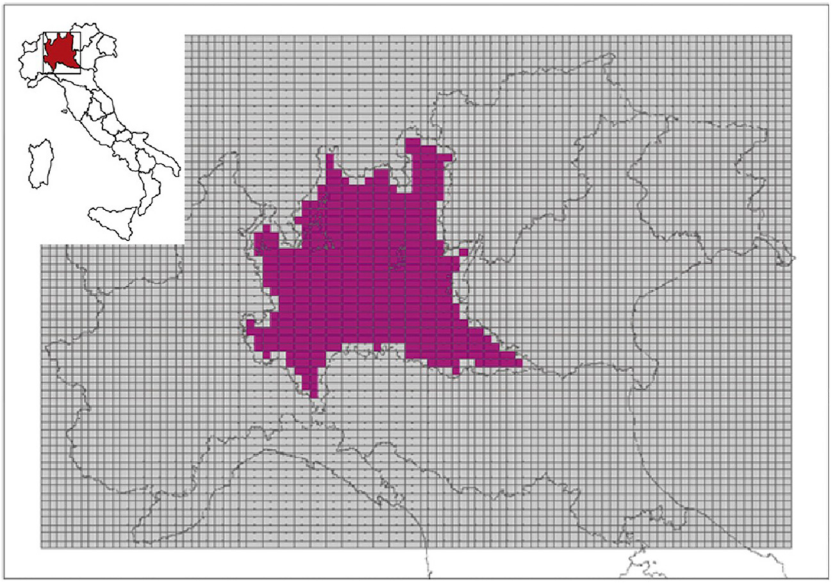

Fig. 2. Lombardy region study domain.

(Transport Chemical Aerosol Model), a 3D Eulerian model (Carnevale et al., 2008).

3.2. Baseline scenario

The database containing details about the application of abatement technologies over the domain is derived from the GAINS system (http://gains.iiasa.ac.at) and has been already used in the project LIFE+ OPERA (www.operatool.eu). The reference regulatory framework is the Current LEgislation Level of 2020 (CLE2020). Emissions have been obtained by projecting INEMAR (INventario EMissioni Aria, www.inemar.eu) regional database emissions to 2020. The projection considers the values of Activity Level (presence of an anthropic activity) and Application Rate (degree of diffusion/implementation of a technology) provided by the current European and national legislation for the year 2020.

3.3. Population database

Data used to compute health effects for this domain have been taken from the national Italian statistical institute web database (Istituto Nazionale di Statistica, 2018).

4. Results

Three scenarios have been analysed: the base case, corresponding to the Current Legislation (CLE) scenario expected by the European Legislation for the year 2020, and two scenarios assuming a reduction of 25% (Scenario A) and 50% (Scenario B) of the breeding activities over the domain.

4.1. Health impacts of PM exposure

Table 1 shows, for five PM_{10} precursors considered (NOx, VOCs, NH_3, Primary PM) absolute and relative difference in emission reductions between CLE and the two reduced scenarios. The Table also includes, in brackets, the uncertainty considering a ± 5% variation of the breeding activities.

The NOx, VOC and Primary PM (PPM) emissions reduction, where different from zero, are almost negligible. As expected, knowing the emission distribution of the breeding sector, NH_3 emissions are those mostly affected by the animal reductions, with an emission decrease for scenario A and B, of 24.5% (19.6%–29.4%) and 49%, (44.1%–53.9%), respectively.

It is possible to assess where such reductions are located by looking at the NH_3 emission maps for the three scenarios in Fig. 3. Since breeding is the macro-sector to which almost the entirety of NH_3 emission is allocated, and since such activities are mainly clustered in the southern part of the region, the emission reductions are located precisely in this area.

The MAQ system is then used to assess the effect of these emission reductions on PM_{10} concentrations. Fig. 4 shows the yearly mean PM_{10} concentrations over the domain. Concentration reduction can be appreciated mainly in the southern part of the domain, where NH_3 emissions are reduced. In these areas, the cell with the higher PM_{10} reduction reaches 5.34 $\mu g/m^3$ for Scenario A and 10.04 $\mu g/m^3$ for Scenario B.

Table 2 shows the YLL due to the population exposure to PM_{10} concentrations. Comparing absolute values and differences with respect to CLE, it is clear that the reductions are not high over the urbanized domain. However, the improvement is significant in the rural areas with high PM_{10} concentrations where the reductions are localized. The

Table 1
Scenario analysis: PM_{10} precursor emission reduction with respect to the CLE scenario.

		NOx	VOC	NH_3	PPM10
CLE emissions [kton/year]		96,248	270,535	106,260	18,263
Scenario A	Absolute emission Δ [kton/year]	149 (119–179)	11,796 (9,437–14,155)	26,039 (20,831–31,246)	104 (83–125)
	Percentage emission Δ [%]	0.2% (0.1%–0.2%)	4.4% (3.5%–5.2%)	24.5% (19.6%–29.4%)	0.6% (0.3%–0.7%)
Scenario B	Absolute emission Δ [kton/year]	299 (268–328)	23,591 (21,232–25,950)	52,077 (46,869–57,285)	209 (188–230)
	Percentage emission Δ [%]	0.3% (0.3%–0.3%)	8.7% (7.8%–9.6%)	49.0% (44.1%–53.9%)	1.1% (1.0%–1.3%)

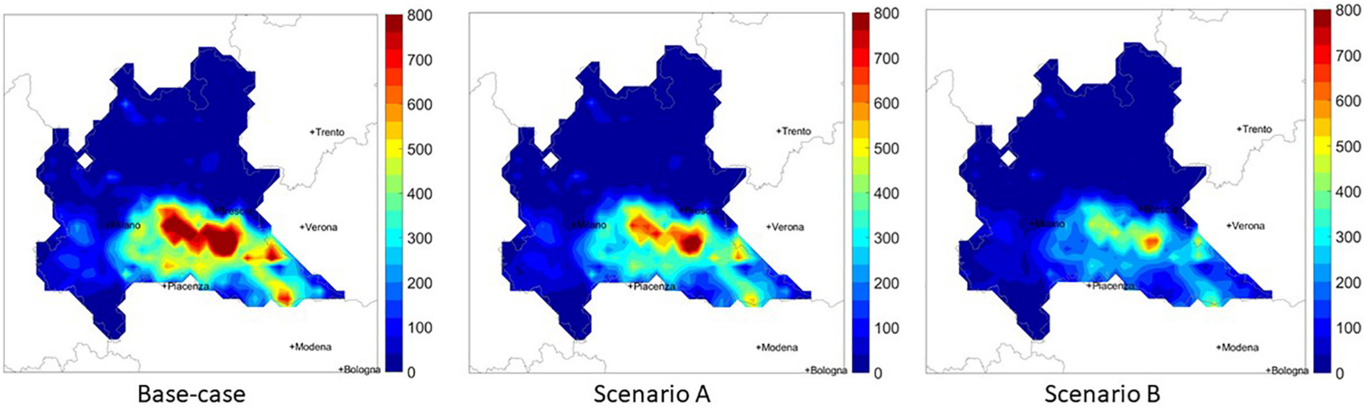

Fig. 3. NH_3 emissions [kton/year] estimated for the base-case and the protein intake reduction scenarios of A) 25% and B) 50%.

same table also includes the impact on avoided premature deaths. The conversion from the YLL metric to premature deaths has been obtained through an approximation of the conversion factor as in Holland and Watkiss (2002). Such conversion is calculated on the YLL value ascribable to $PM_{2.5}$. In this study, we made the conversion based on PM_{10} values. This approximation is justified by the fact that PM_{10} contains the $PM_{2.5}$.

4.2. Co-benefits for GHGs reduction

Besides the impacts that the reduction of animals can have on PM levels, and its related health impacts also GHG emissions are affected by these strategies, being breeding a relevant CH_4 emitting sector. The effects of the two scenarios on CH_4 emissions values are equal to a 12 (9–15%) and 24% (22–27%) reduction for Scenario A and B, respectively.

4.3. Metabolic health effects

The preliminary analysis of data from 6381 US men and women aged 50 and above (NHANES III database) shows that a reduction in dietary animal protein intake is associated with a significant reduction in YLL. Using the equations described in Section 2.1, we estimated the avoided YLL for both reduction scenarios. However, since the effects on YLL are obtained below the 10% threshold of protein content over the total caloric intake, we estimate 9,212 avoided YLL/yr and 815 deaths/yr reduction and the attributable fraction results equal to 0.02 for citizens between 50 and 65 years old.

Even if both metabolic and PM exposure health impacts have been computed in terms of YLL, since the methodologies are different, with different origin and uncertainties, a sum between YLL gained due to reduced protein consumption and YLL gained due to reduced PM_{10} exposure is not consistent and should be avoided.

4.4. Social acceptability to change dietary habits

As reported in Section 2.3, the personal engagement for changes in the dietary habits is analysed in order to identify specific improvements in terms of reduction of premature deaths as a form of compensation to motivate the respondents to change the status quo of dietary habits towards a more sustainable lifestyle. In this study, the reduction of premature deaths has been computed by the MAQ system as described in Section 4.1 (Table 2).

As mentioned, three different clusters of citizens have been identified, being characterized by different attitude towards a reduction in the consumption of meat and dairy products, of the reduction of premature deaths linked to air pollution and towards environmental awareness and intention.

In particular, Cluster 1 members, corresponding to 43% of the sample, are highly sensitive to the cost of a policy measure as well as to the distribution of the cost, showing a preference for the “poor pay less” principle. They are not interested in policies implying a decrease in meat and dairy products consumption. This could imply that they would not change their eating habits even if this would be compensated by a reduction in premature deaths. Cluster 2 respondents, the 29% of the sample, show an important negative sensitivity to a change in eating

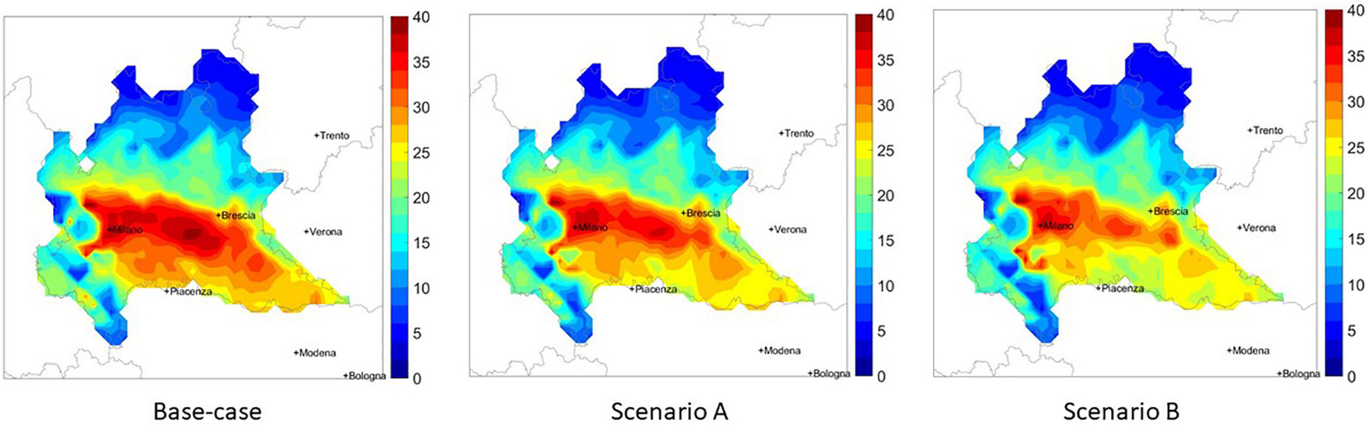

Fig. 4. Yearly PM_{10} mean concentrations [μg/m^3] for the base-case and the protein intake reduction scenarios of A) 25% and B) 50%.

Table 2
Total YLL avoided over the region and yearly avoided premature deaths of the Lombardy region population for CLE and two reduction scenarios of A) 25% and B) 50%. The uncertainty is given in brackets.

	Avoided YLL for year	Avoided premature deaths for year
Scenario A	3,622 (2,889–4,367)	724 (577–873)
Scenario B	7,477 (6,675–8,305)	1,495 (1,335–1,661)

habits if this is not compensated by other benefits and are favourable to the "polluters pay more" principle. A significant number of respondents, 28% of the sample, belonging to Cluster 3, are highly e positively sensitive to a dietary change, also if this would imply higher costs. It is likely that members of this cluster are more focused on the direct benefits of a healthier diet with reduced meat consumption than on the related environmental issues.

Given that members of Cluster 1 must be considered unwilling to change their eating behaviour at any rate, while members of Cluster 3 are already keen on taking up healthier habits, we focused our analysis on members of Cluster 2, i.e. that 29% of the population who might change her/his dietary habits only after compensation, i.e. the reduction of premature deaths.

Applying figures in Table 2 to the Cluster 2 sample and assuming equal sensitivity towards a decrease in meat and dairy consumption between the inhabitants of Lombardy and those living in the rest of Italy, we estimated that, with reference to the Scenarios:

- in order to avoid 724 premature deaths in the Lombardy region, each individual in this Cluster 2 would be willing to reduce her/his meat and dairy products intake of a minimum of 12% to a maximum of 13%, corresponding to about 3 days (2.43–2.65) of consumption per month;
- in order to obtain a reduction of 1496 premature deaths, the reduction in meat and dairy intake would be of a minimum of 24% to a maximum of 26% with respect to the baseline scenario, corresponding to about 5 days (5.02–5.48) per month of abstention.

The estimation of the marginal rate confidence intervals is performed using a bootstrap method based on the Krinsky and Robb (1986, 1990) parametric sampling scheme, widely employed in literature (Gatta et al., 2015).

On the base of these figures we can assess the social acceptability of the two scenarios. As shown in Table 3, the animal protein consumption for the base scenario and the two scenarios considered in this study has been evaluated for three clusters.

Considering no change for Cluster 1, and a conditional change for Cluster 2 as described above, this implies that Cluster 3 could contribute to the reduction required in Scenario A, waiving the 75% of its animal protein intake. The reduction required in Scenario B is not attainable, since the sum of Cluster 1 and Cluster 2 consumption exceeds the Scenario conditions (50%).

Table 3
Percent of animal protein consumption over the total calorie's intake for the three clusters in the three scenarios.

	Base scenario	Scenario A	Scenario B
Cluster 1	43%	43%	43%
Cluster 2	29%	25%	22%
Cluster 3	28%	7%	−15%
Population total animal protein consumption	100%	75%	50%

5. Conclusions

In this study we assessed the co-benefits of a change in dietary habits in the Lombardy region (northern Italy), though an integrated modelling approach. We assumed two scenarios implying a reduction down to below 10% of the protein intake over total calories over all the population of the Lombardy region. The two scenarios assume a reduction of 25 and 50% of the current breeding activities, respectively, as a consequence of the dietary changes.

Based on the results obtained though the MAQ system, we assessed that both scenarios produce a significant but not decisive health benefit due to lower PM_{10} population exposure in the Lombardy region in terms of avoided premature deaths for year for both scenarios (724 and 1,495 respectively). Furthermore, an animal protein intake reduction is estimated to give a metabolic health benefit of the same order of magnitude of that due to PM exposure (815 avoided premature deaths for year).

While, all the Lombardy population would benefit from the PM_{10} exposure reduction, the metabolic benefits would concern only individuals who are reducing their protein intake.

Another general environmental benefit is that related to the reduction in CH_4 emissions, estimated to be 12% and 24% for the two scenarios, respectively.

According to the results of a large DCM survey carried out in Italy, there is a wide heterogeneity in the willingness of the population to change their eating habits. A large percentage of the population (43%) is not interested in changing its eating habits at any rate. The 29% of population, that is available to change its eating habits only after a compensation in terms of avoided deaths, is available to take over just a part of the reduction (14 and 24% for a 25 and 50% protein reduction scenario, respectively). The remaining 28% is positively sensitive to a change of diet. On the base of these assumption we assessed that only Scenario A is socially acceptable, while conditions of Scenario B are not socially accepted.

Therefore, decision makers should consider putting in place end-of-pipe and energy measures in order to reduce NH_3 and CH_4 emissions from the breeding activities, going further the current EU, 2016/2284 directive on National Emission Ceilings (NEC) and European Green Deal (COM(2019) 640 Final, 11.12.2019). A future extension of the work could regard the consideration of morbidity indicators, in addition at the mortality one, in order to assess the thorough health impact.

CRediT authorship contribution statement

M. Volta: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision. **E. Turrini:** Formal analysis, Investigation. **C. Carnevale:** Investigation. **E. Valeri:** Formal analysis, Investigation. **V. Gatta:** Formal analysis, Investigation. **P. Polidori:** Investigation. **M. Maione:** Conceptualization, Writing - original draft, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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