The current document describes the model following the recommendations of the Overview, Design concepts, Details, and Decision-making (ODD+D) (1).

1 Overview

1.1 Purpose and overview

The purpose of the model is to explore the dynamics whether contextual spillover effect would lead to more plant-based protein consumption from worksite to home settings, after implementing a dietary intervention aiming at increasing the consumption of plant-based protein at worksite canteen. The audience of the model is scientists and policy makers interested in food environment, consumption behaviors, and dietary (protein) transition.

The model is coded in Netlogo (version 6.4.0).

The model includes a population of 1368 working age individual agents with characteristics loosely based on adults participants from the Dutch National Food Consumption Survey (DNFCS) between 2012 and 2016. The effect of the worksite canteen dietary intervention is the probability of the consumption of vegetarian meals among non-vegetarian individuals during lunch. Depending on the effect size of the intervention at worksite and decision-making rules of the dietary behavior, the cross- contextual spillover effect will be modeled as outcomes of interests of this agent-based model (ABM). The primary outcome of the ABM would be the average percentage of plant-based protein consumed at dinner at population level after three years of intervention.

1.2 Entities, state variables and scales

The ABM focuses on the decision-making and interactions of individual agents, who are adult individuals making decisions about what types of meal to consume at lunch and dinner. And based on the types of meal consumed at lunch and dinner, a subsequently average plant- and animal- based protein intake can be calculated based on empirical data. For lunch during weekdays, there is a running dietary intervention at the worksite canteen targeting consumption of vegetarian meals, the employed agents make their meal decisions based on the effect size of the intervention and their own dietary identity and habituation; the unemployed agents make their meal decisions based on their own dietary identity and habituation. For dinner throughout the week and lunch during weekends, all agents make their meal decisions based on the carry-on effect of the dietary intervention, and individual, social, temporal, situational, and habitual influences associated with dietary behavior.

The model design of this ABM is inspired by practice theory (PT) (2-4) and identity process theory (IPT) (5) and parameterized with empirical data as much as possible.

There are three broad categories of elements of practices, namely materials, competence, and meaning. We consider the decision of meals as a dietary practice and the following described each element of the dietary practice based on PT: 1) Materials covers all physical aspects of the performance of a practice, including the human body. It is a sequence of bodily activities involving the usage of material artefacts. For example, an agent may cook a vegetarian meal at home. Materials then covers all kind of activities such as ingredients purchase, preparation, and perform the cooking and serve, etc. 2) Meaning incorporates the issues which are considered to be relevant with respect to that material, i.e. the understandings, motivations and emotions. In case of selecting a vegetarian meal, the relevant meanings are ethics, sustainability, health, price, social status. Someone who always chooses vegetarian meals may be associated with being concerned with animal welfare, environment, and health, or not enjoying the taste of meat. 3) Competence incorporates skills and knowledge which are required to perform the practice. Examples are cooking skills, and knowledge about vegetarian ingredients and meals. There are two basic characteristics of social practices: they are routine behavior and they are socially shared. Based on these two characteristics and for the sake of simplicity, we have extracted two abstract processes from the PT and modeled in ABM: habituation and exchange meaning.

A routine practice becomes habitual if a practice has a high coherence and the individual does not experience urge to change anything, and reproduce the practice over time. Therefore, one can make a habitual dietary behavior or deviated behavior as a consequence of social interactions and other interferences. This model includes a level of habituation for each individual which increases through an individual's repeated perform habitual dietary behavior. The higher the level of habituation, the higher level of coherence of such dietary behavior, and the lower the chance that the individual been influenced by the factors from inter-person levels and deviated from habitual dietary behavior. Exchange meaning is designed as individuals communicate and exchange about motivations about their dietary practice cross their social networks. This communication may lead to a mutual alignment of the meaning elements of difference individuals within a type of social network.

Identity process theory was abstracted and designed in the ABM as dietary identity, which consists four dynamic dietary identity traits (DIT) representing the four types of dietary behaviors (i.e., vegetarian, pescatarian, flexitarian, and omnivore). Without any influence from interpersonal and institutional level, one should normally follow the dietary behavior that is consistent with the highest dietary identity traits of oneself as a default dietary behavior. The value for each dietary identity trait may be updated in each period based on the social interactions and interactions with the dietary intervention at worksite. Thus, the default dietary behavior and identity may change for some individuals due to interactions, which simplifies the dynamics of dietary identity process derived from social interactions. Details about the dynamics of DIT will be illustrated in "Sub-models" section.

The social influence or interpersonal influence are designed through two types of social networks. Individual agents are linked in a three-layer social network: fixed friend and household networks and dynamic eating networks that may be part of their friend or household network. Individuals interact with their friends and household networks, to exchange meaning of their default dietary behavior as well as the taste preferences, they can adapt their meaning and taste preferences to be more similar to their social network members. Individuals interact with their eating network to negotiate the dining location and meal selection. Based on the interaction with the eating network, individuals can decide if they would adapt their DIT values.

The types of meal consumed are consistent with the four types of dietary behavior. These types of meal are defined as omnivore (including meat, fish, eggs, and dairy), flexitarian (including the same foods as omnivores, but not eating meat daily or eating less than the average consumption of meat) (6), pescatarian (including fish but not meat), vegetarian (including eggs and dairy, but not meat or fish). The animal- and plant- based protein contents of each type of meal is calculated based on the consumption data from DNFCS. Since the focus is on the contextual spillover effect of the dietary intervention at worksite canteen to the dinner meal process integrating various social, temporal, and situational factors during the decision-making of a dietary behavior. We do not specify foods or recipes, and individuals are assumed to know the existence of all types of diets. Moreover, the availability of all types of meals are not restricted as those meals are quite accessible and available for the study population.

Table 1 illustrates the attributes that characterize these entities.

Table 1. Individual a) parameters and b) state variables.

a. Parameters (Endogenous attributes)

Parameter	**Description**	**Data Type and values**
ID	Individual participant's id.	String
Sex	Sex of the individuals.	Binary [male, female]
Age	Age of individual agents in years.	Ordinal [18, 60]
Employee?	If the individual is employed.	Boolean [yes, no]
Education	Highest degree attained.	Categorical [low, middle, high]
Household size	The number of persons in the individual's household.	Categorical [one person, two to three persons, four persons, five or more persons]
Hh-network-member?	Is the individual a household member with another.	Binary [yes, no]
Friend-network-member?	Is the individual a friend member with another.	Binary [yes, no]

b. State variables (Dynamic attributes)

State variables	**Description**	**Data Type and values**	**Symbol**
Times-intervention	The number of times that an individual consumed vegetarian meal at worksite canteen.	Ordinal [0, timesteps]	τ
Household-alpha	Personal susceptibility towards the influence of other household members in the same household network.	Numeric [0, 1]	a_s
Friend-alpha	Personal susceptibility towards other friend network members.	Numeric [0, 1]	a_s
Price-sensitivity	Sensitivity to price when considering following a type of diet.	Numeric [0, 1]	P
Persuasiveness	Individual's persuasiveness towards other social network members.	Numeric [0, 1]	ps
Dietary-identity	An individual's default choice of types of meal/diet.	Categorical [vegetarian, pescatarian, flexitarian, omnivore]	D_i
Habituation	The degree of habit of the default types of meal/diet of an individual.	Numeric [0, 1]	H
Dietary-identity-traits	List of four values corresponding to four types of meal/diet, the highest value is consistent with the dietary identity.	Numeric [trait-vegetarian (0, 1], trait-pescatarian (0, 1], trait-flexitarian (0, 1], trait-omnivore (0, 1]]	T_d :[T_{veg}, T_{pes}, T_{flex}, T_{omni}]
Environmental-meaning	The degree to which the default diet is influenced by environmental concerns.	Numeric [0, 1]	EM
Health-meaning	The degree to which the default diet is influenced by health concerns.	Numeric [0, 1]	HM
Animal-welfare-meaning	The degree to which the default diet is influenced by animal welfare concerns.	Numeric [0, 1]	AM
Competence-material	The degree to which the default diet is influenced by the perceived convenience and easiness of preparing meals corresponding to the default diet	Numeric [0, 1]	CM
Taste-importance	The degree to which the default diet is influenced by the taste.	Numeric [0, 1]	TI

Lunch-animal-list	A list of animal-based protein content in grams during lunch meals.	List of numeric values	/
Lunch-plant-list	A list of plant-based protein content in grams during lunch meals.	List of numeric values	/
Dinner-animal-list	A list of animal-based protein content in grams during dinner meals.	List of numeric values	/
Dinner-plant-list	A list of plant-based protein content in grams during dinner meals.	List of numeric values	/
Eating-location-hist-list	A list of situational context (location) of each meal consumed.	List of strings out of [supermarket, restaurant, meal-delivery]	$[L_{supermarket}, L_{restaurant}, L_{meal-delivery}]$
Eating-partner ?	If the individual has a eating partner.	Binary [yes, no]	/
Meal-history-list	A list of types of meal consumed.	List of strings	/
Weekly-eating-schedule	The social context with whom the meal is consumed.	List of strings out of [alone, family, friend]	*W*

Besides the individual's attributes, there are no exogenous drivers in the model during simulations- all parameters and state variables are initialized with empirical data relevant to the study or theoretical grounding of specific scenario. Space is not explicitly included in the model. Given the density of food outlets in the Netherlands, and the similar product combinations available at most of them, food availability likely has a minor effect on overall diet choices, which is the focus of the model here.

One timestep represents one day in this model, and the model is not intended to be run for timescales exceeding 3 years, as the assumptions of fixed social networks would be less realistic, and other socioeconomic and sociodemographic variables are more likely to change qualitatively over that time.

1.3 Process overview and scheduling

The figure below (Figure 1) illustrates the sequence of decision-making and events in simulation. Dashed outlines indicate elements of stochasticity in that part of the process. After initialization, the first timestep of the model is Monday. One timestep on a weekday includes all steps after initialization, and one timestep on a weekend repeats twice starting from "Determine eating network".

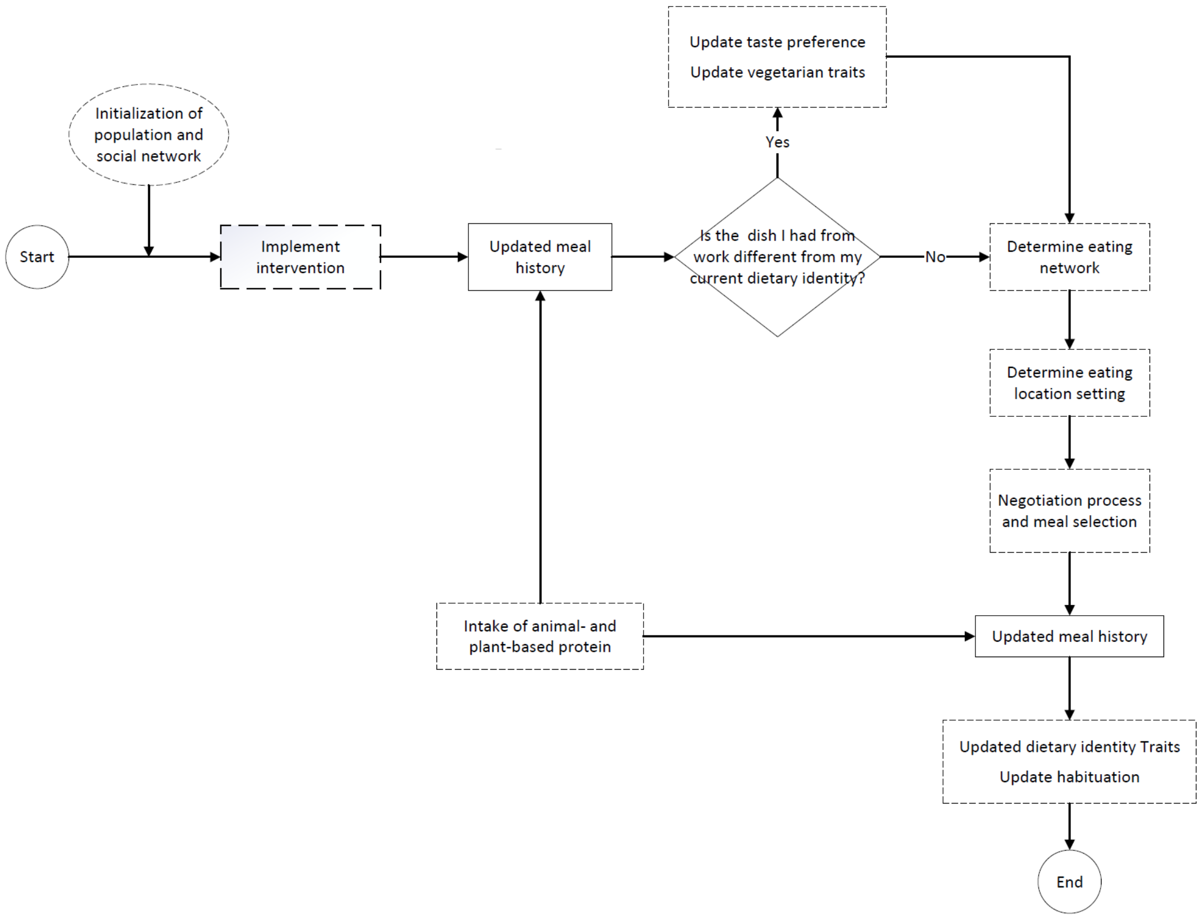

Figure 1. Process overview.

2 Design concept

2.1 Theoretical and empirical background

Shifting diets towards more proteins from plants is not only an essential part in the "Protein transition movement" promoting sustainable, equitable, and balanced protein system (7), but also in line with the "EAT-LANCET" commission promoting sustainable and healthy diet (8). Such a shift would benefit both public health and planetary health. The role of food environment is essential to facilitate the transition towards more plant-based diets, reduce meat consumption, and hopefully achieve the ratio of animal- and plant- based protein intake to 40/60 (9). However, individual dietary behavior and consumption choices are complex dynamic process determined by factors at different social-ecological levels, including individual, interpersonal, organizational, community, and policy levels (10). On the other hand, food environment is also a multi-faceted multi-stakeholder system which could be targeted by various types of interventions, campaigns, and policies (11). According to literature, the mostly practiced strategies to modify food environment and subsequently modify consumer's dietary behaviors are 1) tax on unhealthy food products, 2) subsidies on healthy food products, 3) increase availability of healthy food products, 4) marketing and mass media campaign on healthy food products (11, 12).

Due to restriction of time, human, and fiscal resources, policymakers often design and implement policies based on collective empirical evidence. Nevertheless, it is still uncertain and unclear to policymakers regarding to what extent and how changes of food environment can achieve (towards) the transition to the ratio of animal- and plant- based protein intake to 40/60 by 2030 (13). This is due to 1) the lack of empirical evidence about evaluation of these implemented interventions, campaigns, and policies; 2) meat consumption is a social phenomenon and it is challenging to design an intervention that captures the complexity and dynamics among individuals, inter-individuals, and the food environment; 3) available empirical evidence are often a mixture of quantitative and qualitative data from difference population. Therefore, the directed acyclic graphs-informed regression approach would not be feasible in answering this research question. The micro-simulation approach would also not capture the dynamics and interactions between individuals and the food environment.

The agent-based modelling (ABM) is a computational model of interaction between heterogeneous agents embedded in given social structure where macro-level outcomes are studies as dynamic consequences of agent interaction (8). Unlike DAGs- informed regression modelling that consider the linear relationships, ABM focus on largely unpredictable, unforeseen, unplanned aggregate outcomes due to nonlinear causal relationships between interacting agents (14). ABM can also integrate both qualitative and quantitative data into one model and provide insight into how a system would behave according to different policy scenario or behavior rules. Despite its born in the 1940s, ABM has rarely been applied in the public health nutrition domain, compared to other domains such as sociology and ecology. Fortunately, researchers start to realize the need for incorporating a complex system model of evidence-generating for public health research, policy, and practice (15).

Evaluation of the effects of interventions focusing on modifying food environment is often challenging because of restricted timeframe, human resource, and methodological limitations. Therefore, "direct effects" after the end of the intervention period are often measured and reported. In order to facilitate the shift towards a more plant-based diet, it would be necessary to evaluate the "aftereffects" of interventions to check the continuity of such effects outside a specific intervention settings. The "aftereffects" is also referred as spillover in literature, which can be further categorized into behavioral spillover and cross-contextual spillover effects. Behavioral spillover denotes the effect from targeted behavior to another behavior in the same domain (e.g., pro-environmental behaviors), while cross-contextual spillover effect represents the performance of a behavior in one context affects the probability of performing the same behavior in a different context (e.g., time, location, and social network). Behavioral spillover effects have been found in many interventions targeting pro-environmental behaviors (16), however, cross-contextual spillover effects has received far less attention than behavior spillover, especially in food environment interventions targeting dietary behavior. In fact, evaluation cross-contextual spillover effect would be even more important for interventions targeting "protein transition", given that the interventions are usually implemented in one specific setting (e.g., worksite and colleagues), while our daily dietary practices happen cross several location and network settings (e.g., home and restaurant, with family and friends).

Health promotions targeting dietary behaviors at worksite are found to be effective (17), including increasing the availability of healthy or sustainable meals, for example, plant-based or vegetarian dishes (18). A year-long large-scale series of observational and experimental field studies have shown that doubling the proportion of vegetarian meals offered increase vegetarian sales by between 41% and 79% (19). Another nature experiment conducted in supermarket found that average weekly unit sales of plant-based products increased significantly (52%, CI 51%-55%) after an intervention period with increased availability of plant-based products (20). On the other hand, little empirical evidence is available regarding the cross-contextual spillover effects of the behavioral change after the intervention of increasing availability at worksite. To our knowledge, there are two qualitative studies that explored the mechanism between cross-contextual spillover effects (21, 22), which could be reflected as a combination of theories of practice and identity process theory (23).

Spillover in theory of practices could be seen as the overlap of practice bundles, as the practice bundles are connected despite time and space and individuals are unique crossing points between practices. In the context of dietary practice, the practice bundle consists of materials (infrastructure and budget of dietary practice), competences (skills and knowledge of a dietary practice), and meaning (perceived values attached to the dietary practice) (23). Spillover in identity process shows that performance of a practice may affect the contents of one's identity that guide the way one interacts with different social-material elements, which might confront with available elements of practice at other settings and involve negotiation with other individuals in the network (23). The four identity principals are continuity, self-efficacy, distinctiveness, and self-esteem. The combined theorical framework of cross-contextual spillover effect would be part of multi-dimensional processes that entail the dynamics of how practices are perpetuated, abandoned, and/or adapted, in combination with the intrinsic and continuous strategies of practitioners to fulfill identity principles. Furthermore, Identity principles influence the probability that spillover effects of practices will (not) occur: interrelation of identity process and changes of the elements of practices(23).

2.2 Individual decision-making

On a weekday, individuals who are not vegetarian and are employed will be randomly allocated/exposure to vegetarian meals from worksite canteen based on the effect size of the canteen meal intervention (as shown in odds ratio) on individuals with different dietary identity. After consuming the meal at worksite, they will evaluate the taste and update their taste preference if they have been exposure to a type of meal that does not correspond to their current default dietary choice based on their dietary identity traits. Every individual has a list of four intrinsic dietary identity traits with a score for each trait, namely, vegetarian, pescatarian, flexitarian, and omnivore. It is assumed that the traits are dynamic and fluid and individuals will act based on the dominant trait. Besides updating taste preferences, when it is time to reflect the effect of dietary intervention after a continuous exposure, each individual's vegetarian dietary identity trait will also be updated depending on the amount of vegetarian meals they have consumed at canteen at the time of reflection.

After the canteen meal, they will go home and decide on which network they will eat with and they will eat either alone, with household members, or with friends. Then based on preference of eating location from the eating network, each eating network will decided on a location to eat, either cook and eat at home, dine out in a restaurant, or use meal delivery service.

After deciding the social and situational context of the meal consumption scenario, the individuals will negotiate with the eating network about the type of meal to choose based on their current dietary identity traits and the default dietary choice. Individuals with vegetarian default diet will always follow their dietary identity and choose vegetarian meal regardless of the social and situational influence. For individuals with non-vegetarian default diet, when the eating at home, they will follow the dominant dietary identity trait of the current eating network, when eating not at home, their probability of following the dominant dietary identity trait would depend on the degree of habituation of their current default diet.

After the evening meal, every individual starts to adapt their dietary identity traits. When the previous consumed meal type is consistent with their current default diet, the corresponding dietary identity trait will increase. For those with default vegetarian diet, if they were in a dominant non-vegetarian diet eating network, their vegetarian dietary identity trait would also increase. When surrounded by omnivores, their omnivore dietary identity trait would decrease. For those with default pescatarian diet, if the dominant dietary identity trait is omnivore, their pescatarian dietary trait would increase. When the previous consumed meal type is not consistent with their current default diet, the dietary identity trait corresponding to the previous consumed meal type would increase. The increase and decrease rate is based on a logistic growth function taking into account the individual's susceptibility to the type of social network during the last consumption and the degree of habituation of the current default diet.

If the two meals from previous day are consistent with the current default diet, then the habituation of the current default diet would be increased. When it is time to exchange meanings with the network members, each individual will evaluate how close their meanings are with the network members, the close the meanings, the higher increase of the current default diet would be. Last, at the end of each time point, individual will check if the highest value of the dietary identity traits is still consistent with the current default diet, if not, then the current default diet will be changed to the type of diet corresponding to the current highest value of the identity traits, additionally, the habituation will be set to zero because one has started a new dietary practice.

When it is a weekend day, the decision-making process starts from deciding the social and situational context of the meal consumption scenario, and then repeat once.

2.3 Learning

The procedures of updating habituation, dietary identity traits values, and default diet after exposure to intervention and social, situational, and temporal influence of a eating network, could be conceptualized as a process of individual learning. Due to continuous exposure to intervention and the influence from network members, individuals learn to like the types of meal that are not consistent with their default diet because of increased familiarity with the type of dish in terms of taste and the recipes they are exposed to as well as through the communication with other members during eating episode. Therefore, their personal dietary traits corresponds to the type of dish will increase, which subsequently increase the likelihood of changing their own dietary identity.

On the other hand, the degree of habituation reflects the attachment one has towards the default diet. Thus, the higher the habituation, the less likely one would learn and adapt their default diet to other types of diet (24, 25).

2.4 Interacting

Interactions take place between the employed individuals and the intervention from worksite canteen, and among social networks members. It is assumed that the influence of the household links are stronger than friend networks, so the susceptibility to a household eating network would be stronger. The process of reflection on the influence of the dietary intervention, updating habituation, dietary identity traits, and exchange meaning during interactions is modeled explicitly. The communication is represented through the updating of dietary identity traits and habituation after one time step. The structure of the household and friends social networks are initially imposed with two variations, but as links in the small world friend network can change, the structure becomes an emergent outcome of the simulation.

2.5 Collectives

The household and friend networks are explicitly defined during initialization of the simulation and they are maintained constant during each run of the simulation. Each household member is connected with every other members of the household, the same is applied for friend network. There is no overlapping between household and friend network, so an individual's household members are not part of their friend network. For dinner and weekend lunch, the eating network of each meal is part of the social network which is dynamic, depending on the type of social network the individual chooses, so the influence on dietary identity traits are restricted within the current eating network. However, exchange meaning happens with all social network members (i.e., both friends and household members).

2.6 Heterogeneity

In principal, individuals are heterogenous across all variable (table 1) and social network links. As individual variables are initialized based on either individual level or aggregated distributions from empirical data, there is a possibility that may share some variable values. Every individual follows the same overall decision-making process for diet selection, interaction, and changes to identity traits and habituation due to this interaction. However, given the differences in state variables and parameters, the exact outcome of these decisions will vary considerably across individuals. Additionally, the stochastic elements present in decision-making and influence mean that even identical individuals in the same situation could make different decisions, and individuals may influence each other differently.

2.7 Stochasticity

Stochasticity is present in the model at initialization, every decision-making procedure, interaction, updates to dietary identity traits and habituation, and record the intake of animal- and plant-based protein. During initialization, some attributes of the individuals are assigned explicitly based on DNFCS, while some attributes are based on distributions and ranges from empirical data source. Therefore, the precise value assigned for each attribute to a given consumer is not fixed.

During the simulation go process, individuals who are employed will be randomly assigned to consume a vegetarian meal based on the effect size of the intervention. Then, there is a stochastic error term in the updating employee’s taste preferences of a diet they have tried at canteen in that timestep, to represent different experiences with context and other aspects not modeled here that may influence taste. The influence of the intervention is modeled based on the function of the degree of habituation of current default diet and the degree of successful exposures at the time of reflection. Moreover, interaction between individuals during dinner and weekends lunch is stochastic, in terms of the formation of eating networks and the outcomes, the individuals have a probability of being part of a household and friend social network based on certain likelihood but is not fixed for each time step. Also, there is a probability of deviation from routine weekly eating schedule. Furthermore, the individuals have choices of accepting or declining other individuals influence or adjust the degree of influence on a certain dietary traits and habituation based on the current habituation, susceptibility to social network, similarity of the meanings and taste preference with other network members.

To record the intake of animal- and plant-based protein intake, the amount of animal- and plant-based protein is calculated as an input based on distributions of DNFCS. The distributions of animal- and plant-based protein content is further categorized based on the temporal and situational context. However, as the record is based on distribution, the precise value assigned for each meal to a given individual is not fixed.

2.8 Observation

At each time step, the consumed meals, animal- and plant-based protein per meal, location, and the structure of the eating network will be recorded. The average percentage of plant-based protein consumed at dinner, the average percentage of plant-based protein consumed at lunch, and the average dietary identity traits are of interests. The choice of different social network structures, which partially determines processes of social interaction, is another emergent outcome that can influence this.

3 Details

3.1 Implementation details

The model is implemented in NetLogo v6.4.0.

3.2 Initialization of population and input

Initialization of the population will be based on the demographic characteristics of the adult population from DNFCS 2012-2016 explicitly, including id, age, sex, education attainment, employment, household size, self-reported dietary identity (only for vegetarians and pescatarians), and mean animal- and plant-based protein consumption at lunch and dinner (Table 1). Household members and friends are connected at initialization and remain connected for the duration of the simulation. Two forms of household and friend networks are coded for this model. The initial dietary identity traits are randomly generated with the highest value corresponding to the self-reported dietary identity from DNFCS and the initial percentage of flexitarian from the stochastic parameters.

Several other data sources were used to parameterize the other attributes to reflect the Dutch context. These included demographic data on household incomes, surveys on motivations and personality traits of individuals with different dietary identity, and questionnaires about weekly social and situational eating schedule. The psychological and behavioral rules of the model are not explicitly linked to the cross-contextual spillover effect of a dietary intervention due to lack of empirical evidence, as they are mostly reported based on qualitative general social, behavioral, and psychological theories. However, we used equivalent empirical evidence to initialize those rules with functions that roughly matches the evolvement of those rules reported from qualitative studies.

The input data the model use after initialization is the intake of plant- and animal- based protein per types of meal, which varies depending on the location of consumption and the time of the consumption. The data for protein intake are aggregated from DNFCS 2012-2016.

3.3 Sub-models

3.3.1 Simulate intervention effect size

On a weekday during lunch time, the model starts with the output of a canteen intervention that nudged employees to choose a vegetarian meal. The intervention could be any format that aiming at restructuring physical micro-environments or food environment to increase the plant-based protein consumption. The output/effect size of the intervention is modeled as the percentage of randomly selected employed non-vegetarians consuming a vegetarian meal during this workday. The default effect size of the intervention is 0.5, meaning that half of the employed non-vegetarians would be randomly selected to consume a vegetarian meal. We have decided to start from the effect of the intervention and not restricted to a specific type of intervention due to the inconsistent effect size reported from a wide range of interventions designs that cannot be synthesized as high-quality evidence-based output (26, 27).

There are some experimental interventions that followed, to some extent, a randomized control trial, and quantified the effect size of the intervention. For instance, interventions that changed the default menu to meat-less meals found that the intervention group had lower odds of selecting meat options than the control group (Odds ratio (OR) 0.24, 95% CI 0.18-0.36) (28); or the meal purchases over intervention period had 0.12 times the odds of containing meat compared with meals purchased during the control period (OR 0·12, 95% CI 0·08–0·18) (29). Moreover, another intervention manipulated the menu as vegan default, and found that participants in the intervention group were 4.1 times likely to choose meatless meals, compared to those in the control group (27). If the intervention was to manipulate the information provided of meat or alternatives, the intervention group had 0.83 times the odds of choosing meat meal compared with the control group (OR 0·83, 95% CI 0·71–0·98) (29). Another study investigated only the interventions to reduce meat consumption by appealing to animal welfare and reported a reduction of meat consumption, purchase, or related intentions in short term with a meta-analytic mean risk ratio [RR] = 1.22; 95% CI: [1.13, 1.33]) (30). Nevertheless, the majority of existing experimental studies aiming at a more sustainable food environment to promote more plant-based protein consumption suffer from the intervention design flaws. Thus, it remains a challenge to measure, quantify, and attribute the effect of such interventions.

3.3.2 Update taste preference

At the end of the workday lunch ("eat-eat-work-canteen"), employed individuals update their perception of taste of each type of diet/meal as the following (31): $TI_t = \begin{cases} TI_{t-1} + \frac{1-TI_{T,t-1}}{1+\varphi e^{-k\tau}}; & i = 0 \\ -1 + \frac{TI_{T,t-1}+1}{1+\varphi^{-1} e^{\varepsilon-k(t-\tau)}}; & i = 1 \end{cases}$

On each weekday, employed individuals would update their perception of "taste-importance" *TI*, where *t* is the current timestep, *i* is a binary variable indicating if they are targeted by the intervention (consuming a vegetarian meal), *k* ("Taste perception change rate") is a parameter determining how much the effect of the intervention decreases in the taste preference of the type of meal corresponds to current dietary identity when targeted by the intervention, or increases when not targeted by the intervention, τ is how many times the individuals are targeted by the intervention, φ is a parameter that determines the gradient of change from the previous value ("Taste perception change gradient"), ε is a stochastic error term to allow individuals to have a positive or negative experience from the intervention ("Taste perception change error").

3.3.3 Reflect the effect of the dietary intervention

After the intervention is implemented, we assume that with the accumulation of exposure to the intervention, the employed individuals will start to reflect on their vegetarian traits T_{veg} when it is time to reflect on the accumulated intervention experience in the past timesteps as follows:

$$T_{veg,tr} = \frac{1}{1 + \left(\left(\frac{1}{T_{veg,tr-1}}\right) - 1\right) \times e^{(-((1-H_{tr-1}) \times \gamma))}}$$

When the timesteps reaches the designated timeframe *tr* to reflect on the accumulated effect of the intervention, where *H* is the habituation, γ is the accumulated target from the intervention in the past timesteps meaning the ratio of the frequency of being targeted (τ) divided by the current timesteps. The reflection of the intervention effect would always be positive because it is been observed that after being repeatedly exposed to a more sustainable dietary behavior, both for consumption of meat substitutes (32) and organic food purchases (33), the impact on either liking or purchase behavior of such behavior was positive.

3.3.4 Setup eating network

The second meal of each day or each timestep is evening meal, where the individuals will first form a eating network with either their friends or their household members. The eating network is scheduled and updated every week or every 7 timesteps, i.e., weekly-eating-schedule (W). A survey from the Dutch Nutrition Center in 2019 found that there was significant difference of the evening meal schedule between single household and non-single household (34). Therefore, the weekly eating schedule is modelled based on a probability approach using the reported frequency of eating schedule for single household and non-single household separately (Table 2). A stochastic 10% of deviation from the default eating schedule is introduced allowing individuals to fluctuate from the schedule eating schedule.

Table 2. Input probability of weekly eating schedule.

Household type	Single	Non-single
Alone	80%	2%
Household members	9%	96%
Friends	11%	2%

After determining the type of eating network, either alone, with household members, or with friends, individuals will start to team up from their initial social network based on the size of the current eating network. The size of the eating network (*n*) of the current meal is based a reported observational statistics of *Dunbar R.I.M.*, where a eating network size follows a normal distribution with mean 3.6 and SD 1.3 persons (35).

3.3.5 Choose eating location

After the eating network of the current meal is installed, the individuals within each eating network will decided upon the location of the current meal, meaning cooking and eating at home, dining out in a restaurant, or use meal delivery services. The empirical ground of the selection of eating location was also derived from the survey from Dutch Nutrition Center, where 21% of the participants reported visiting a restaurant weekly, while 38% of the participants reported using meal delivery service weekly (34). Based on the survey, we further assumed that if participants did not dine in a restaurant weekly, they would do so monthly; and for those who did not use meal delivery service, they would do so every three weeks. Thus, the overall probability of dining in a restaurant and using meal delivery service per week are $L_{restaurant} = \left(\frac{21}{7} + \frac{79}{28}\right)$ and $L_{meal-delivery} = (\frac{38}{7} + \frac{62}{21})$, respectively.

Apart from the global probability of determining eating locations, the average preference to eat out of the current eating network is also crucial. The preference to eat out ("*Pre*") is determined by the price sensitivity ("*P*") of the individuals, which is a score between 0 and 1 with a higher value indicating a stronger preference to eat out. Therefore, the probabilities for eating location L_x is as following:

$L_x = \frac{\left(\left(\frac{\sum_{i=1}^{n} Pre_i}{n}\right) \times P_l\right)}{0.5}$, where *n* is the size of the current eating group, *Pre* is the preference to eat out, P_l is the global probability of weekly eating location ($L_{supermarket}$ $L_{restaurant}$ $L_{meal-delivery}$), 0.5 is the mean and median value of preference to eat out. This equation calculates the probability of dining in a restaurant and using meal delivery service, simultaneously, the probability of eating alone could be derived.

3.3.6 Person select meal

The meal selection is a tradeoff between follow the average and its own habituation of current type of diet, which abstracts the empirical observations from multiple studies. The influence can be categorized into three social-ecological levels: intrapersonal (habituation), interpersonal (social network), and community (eating location) levels.

Interpersonally, the higher the habituation of consumption a type of meal, the less likely the influence from other social-ecological levels would yield a material change on the dietary behavior. It was shown that consumers with lower levels of meat attachment are more inclined to change their meat dietary pattern away from meat-rich habits, whereas consumers higher in meat attachment appear to eat meat more often, have stronger preferences for meat, and are less likely to restrict meat eating and to change towards a more flexitarian diet (24, 25). We also assume that individuals who are more susceptible towards social norms would be more likely to be influenced by the social network.

At interpersonal level, people tend to adjust their food choices and intake to affiliate with their social network, such as friends and family (36). Correspondently, when eating healthily is perceived as the marker of the majority group, only minority participants are found to eat less healthily (37). Therefore, the in-group influence could lead to changes at the system levels, as Ge *et al.* also found that if people in the same network with the same dietary behavior, the type of dietary behavior will be reinforced with deciding the meal at a group level. On the other hand, if different dietary behaviors exist in the same social network, it will yield positive influence on the different dietary behaviors (38). Whist eaters are also found to be more likely to modify their food choices if opposing eating norms are represented by direct social ties (39).

It is noticeable that the interpersonal social influence is not consistent for all types of dietary identity. Vegetarian peers seem to influence their non-vegetarian co-eaters instead of vice versa; in other words, meat-eaters who are accompanied by vegetarians are more likely to choose a vegetarian dish than meat-eaters who are accompanied by other meat-eaters alone (39). Another study revealed that flexitarians feel they need to justify and fight for their meat-eating behavior when eating with only vegetarians (40).

Besides the influence for the social network, the location of consumption is also important, as people who reduce meat consumption at home might allow themselves to eat meat in the restaurant. Studies also reported that meat consumption was higher when dining out compared to the home and work setting in the same study populations (21, 41, 42), indicating a lower likelihood to adjust to the dominant choice of the social group.

To operationalize the handful of empirical evidence, the following decision-making process has been modelled to simulate individual's meal selection. Within a eating group, the dominant dietary identity is calculated, and vegetarian(s) in each eating group always choose vegetarian meal irrespective to the social network or eating location. For non-vegetarians, if the eating location is at home, they would select the type of meal corresponding to the dominant dietary identity in the eating group. If the eating location is at restaurant or using meal delivery service, the higher the habituation, the more likely they are going to select a type of meal that is consistent to their current diet, otherwise, they would follow the dominant dietary identity in selecting the meal.

3.3.7 Update dietary identity traits and update dietary identity

After person selected the meal, individuals enter the process of reflecting the intention to change their dietary identity, which could reflect on changes in their dietary identity traits. Studies have found that the interpersonal and community level influences do not always lead to behavior change, but rather an intentional change which would accumulate and lead to behavior change eventually (43, 44). The rules of updating dietary identity traits are shown in table 3.

Table 3. Dynamics of dietary identity traits after evening meal consumption.

Dietary identity	Dominant dietary identity (group)	Meal consumed consistent with dietary identity	Dietary identity traits
Vegetarian	Vegetarian	Yes	(+) vegetarian trait
Vegetarian	Omnivore	Yes	(+) vegetarian trait (-) omnivore trait
Pescatarian	Pescatarian	Yes	(+) pescatarian trait
Pescatarian	Omnivore	Yes	
Flexitarian	Flexitarian	Yes	(+) flexitarian trait
Omnivore	Omnivore	Yes	(+) omnivore trait
Pescatarian, flexitarian, and omnivore	Vegetarian	No	(+) vegetarian trait
Pescatarian, flexitarian, and omnivore	Pescatarian	No	(+) pescatarian trait
Pescatarian, flexitarian, and omnivore	Flexitarian	No	(+) flexitarian trait
Pescatarian, flexitarian, and omnivore	Omnivore	No	(+) omnivore trait

The degree of increase or decrease of the designated dietary identity trait (T_d) at timestep t is as follows a logistic function:

$$T_{d,t} = \begin{cases} \dfrac{1}{\left(1+\left(\left(\frac{1}{T_{d,t-1}}\right)-1\right)\times e^{\left(-(\alpha_S \times H_{t-1})\right)}\right)} & ,(+) \\ \dfrac{1}{\left(1+\left(\left(\frac{1}{T_{d,t-1}}\right)-1\right)\times e^{(\alpha_S \times H_{t-1})}\right)} & ,(-) \end{cases}$$

, where α_s is the susceptibility to the types of social network from the initialization, H is the habituation of the current dietary identity. Susceptibility partially reflects the social identity one wants to maintain in a social network with social norms, which emerged as a significant factors for avoiding meat consumption (45).

After updating the dietary identity traits, if the trait with the highest value has changed, the default selection of types of meal will change as well, meaning a transition of dietary identity (D_i).

3.3.8 Update habituation

At the end of each timestep, individuals will reflect the two meals they consumed during the timestep (day). When behavior is performed repeatedly, it becomes habitual and is guided by automated cognitive processes (46). If the two meals consumed correspond to current dietary identity, the habituation of current dietary identity would increase based on a speed of habit formation reported from a meta-analysis and meta-regression (47). In this meta-analysis of various lifestyle interventions, a habit formation plateau of 84 days was found (47), which leads to the habituation growth rate of this model. The habituation growth follows a simple asymptotic process ${H_\mu}^2 = \mu$ that reaches $H_\mu = 1$ when μ is equal to 84 times of consuming the meals corresponding to current dietary identity during the day. Thus, H_μ increases fast for low levels of habituation and becomes slower the more the process reaches the plateau.

If there is a change of dietary identity due to the dynamics of dietary identity traits, the habituation level H_μ is set to *0*, indicating that a new habit is breeding and will form gradually following the habituation growth function.

3.3.9 Exchange meaning

Individuals also communicate about their values based on their own dietary identity within their social network, and gradually, the exchange of meaning within a network may lead to a mutual alignment of meaning of different individuals within the same network. The meanings of dietary identity with its corresponding default selection of types of meal is divided into three dimensions: values attached to animal-welfare, health, and environmental concerns; taste preference; and perceived competence and available materials.

The reflection and exchange of meaning is denoted as the automatic appraisals that can be characterized as unintentional, uncontrollable, and unconscious evaluative processes (48). For dietary behavior, a study found that automatic appraisals differed across attribute dimensions, i.e., perceived taste did not significantly relate to any other dimension, whilst environmental sustainability, health, and animal-welfare that were significantly correlated despite the little shared variance with each other (48).

The values of environmental sustainability, health, and animal-welfare towards dietary consumption have been demonstrated as the driving values in protein transition (49-53).

The importance of liking the taste of the type of meal has also been highlighted as attribute of motivation (49, 50, 53, 54). Following the theory of practice, competence and materials are of equal importance to the values of environmental sustainability, health, and animal-welfare. The elements of competence and materials have also been reported as a barrier of adopting new dietary behavior. These practical difficulties included lack of information for consumers and difficulty to acquire new cooking skills, changes in service provision in collective meal contexts (52-54). The influence of meaning from social network has also been discussed (52) and level of habituation and familiarity would also interfere the alignment of different dimensions of meaning (52, 53, 55).

The operationalization of the meaning exchange, the differences of values of environmental sustainability, health, and animal-welfare, taste, and competence and materials with one's social network would yield a decrease or increase of one's habituation of the current diet. The effect of meaning exchange of each individual i on $H_{i,t-excahnge}$ only occurs when it is time to exchange:

$H_{i,t-exchange} = \frac{\Delta_{i,n,value} + \Delta_{i,n,taste} + \Delta_{i,n,cm}}{3}$, where $\Delta_{i,n,value} = \left(\frac{\left(\sum_1^n \left(EM_n + HM_n + AM_n / 3\right)\right)}{n} \times \frac{\sum_1^n ps}{n} \right) - \left(\frac{EM_i + HM_i + AM_i}{3} \right)$, $\Delta_{i,n,TI} = \left(\frac{(\sum_1^n t)}{n} \times \frac{\sum_1^n ps}{n} \right) - t_i$, $\Delta_{i,n,CM} = \left(\frac{(\sum_1^n CM)}{n} \times \frac{\sum_1^n ps}{n} \right) - CM_i$; n is the network members one has, including both friends and household networks, EM is the environment meaning, HM is health meaning, AM is animal welfare meaning, ps is persuasiveness, TI is taste-importance, CM is competence and material value.

4 Sensitivity analysis

4.3 Determining parameter ranges for sensitivity analysis

For the sensitivity analysis, default values for global parameters were sourced from empirical data where possible, or were estimated from initial testing of the model. For the sensitivity analysis, the maximum and minimum values for assumed variables were set at 50% higher and lower than this ‘default’ value, respectively. For variables with empirical evidence, the maximum and minimum values are assumed based on the mostly likely timespan of range (Table 4).

Table 4. Sensitivity testing ranges of parameters

Variable	Description	Symbol	Data type and range	Default value	Range for sensitivity analysis
Initial number of flexitarians	The percentage of flexitarians among those who are not vegetarian nor pescatarian.	IN_{flex}	Numeric [0, unbounded)	13	[3, 43] (6)
Initial rewiring probability	The probability of rewiring to create a small-world network when setting up the friend social network during initialization.	IN_r	Numeric [0, 1]	0.5	[0.25, 0.75]
Initial age range of a friend network	During friend social network setting up, the max age difference in years of a friend network.	A_f	Integer [0, unbounded)	6	[3, 13]
Initial mean friend social network node degree	During small-world network setting up, the total number of friends a given individual is connected to initially, on average.	N_f	Integer [0, 1368]	4	[2, 6]
Frequency of self-reflection after the intervention	The frequency (days) of a given individual reflects on the effect of the intervention.	tr	Integer [1, unbounded)	21	[7, 77]
Frequency of exchange meanings with your networks	The frequency (days) of a given individual exchange meanings with the social network members.	$t\text{-}exchange$	Integer [1, unbounded)	30	[15, 165]
Habit formation plateau	The number of days to form a habit and become stable.	μ	Integer [1, unbounded)	84	[42, 126]
Taste perception change rate	The rate of taste perception change with exposure	k	Numeric [0,1]	0.01	[0.005, 0.015]
Taste perception change gradient	The gradient of taste perception change from previous value	φ	Numeric (0, Inf)	50	N/A
Taste perception change error	The stochastic error applied to taste perception change when a diet is consumed	ε	Numeric [0, 1]	0.001	[0.0005, 0.0015]

4.4 Model stability

To test whether the model reached a quasi-stable state within a run or across a parameterization, 50 runs were performed with default parameters and all sub-models included for a time span of 3 years. The coefficient of variation (ratio of standard deviation to mean) for each outcome variable was calculated across the runs, to determine the necessary number of replicates to account for the stochasticity in the model, following Lorscheid et al. (56). A final value of 20 replicates was identified as sufficient to cover the stochasticity in the default parameterization. A time span of 3 years was chosen as the maximum tangible duration of real-life intervention.

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