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Waters, James

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A model of the dynamics of household vegetarian and vegan rates in the U.K.

James Waters[*]

Warwick Business School, University of Warwick, Coventry, CV4 7AL, United Kingdom

ABSTRACT

Although there are many studies of determinants of vegetarianism and veganism, there have been no previous studies of how their rates in a population jointly change over time. In this paper, we present a flexible model of vegetarian and vegan dietary choices, and derive the joint dynamics of rates of consumption. We fit our model to a pseudo-panel with 23 years of U.K. household data, and find that while vegetarian rates are largely determined by current household characteristics, vegan rates are additionally influenced by their own lagged value. We solve for equilibrium rates of vegetarianism and veganism, show that rates of consumption return to their equilibrium levels following a temporary event which changes those rates, and estimate the effects of campaigns to promote non-meat diets. We find that a persistent vegetarian campaign has a significantly positive effect on the rate of vegan consumption, in answer to an active debate among vegan campaigners.

Keywords: vegetarianism, veganism, food choice, dietary change, social influence, animal advocacy

[*] E-mail: james.m.waters@hotmail.co.uk

Introduction[1]

There are a number of compelling reasons why a dynamic model of consumption rates of non-meat diets in a population would be valuable when forming social and business policy. Firstly, around the world hundreds of millions of people are estimated to follow a vegetarian diet which avoids consumption of meat (including fish) or a vegan diet which additionally avoids consumption of eggs, dairy, and other products derived from animals (Cooney, 2014, ch.2; Leahy et al., 2010), and governments could use a dynamic model to plan for their future needs, for example in hospitals or other institutional settings. Secondly, the market for products substituting for animal derived products is worth many billions of dollars in the U.K. and U.S. alone (Priority Ventures Group, 2011; Mintel, 2014), and business could use a dynamic model to help project and meet emerging demand. Thirdly, there is an active discussion about whether promoting a vegetarian diet increases the number of people who subsequently adopt a vegan diet (Shephard, 2015; Dunayer, 2004, p.155; Francione, 2010), and a dynamic model can help to inform the analysis.

There are no quantitative dynamic models of the rates of vegetarianism and veganism in a population as far as we are aware[2], although many papers have shown how dynamic processes are relevant for understanding consumption of low- or non-meat diets. Some papers, including McDonald (2000), Lea et al. (2006), Wyker and Davison (2010), and Mendes (2013), demonstrate how individuals have a staged process of adoption, for example based on the transtheoretical model. These models do not attempt to describe adoption dynamics across a population. Other papers have looked at the duration of the transition into non-meat diets or rates of persistence with

[1] Abbreviations used in this article: OLS (ordinary least squares), LSDV (least squares dummy variables), VAR (vector autoregression), and GIRF (Generalised Impulse Response Function)

[2] Based on searches on Google Scholar, Science Direct, Springer, Emerald, and Taylor & Francis.

them (Barr and Chapman, 2002; Hoffman et al., 2013; Beardsworth and Keil, 1991). Again, these papers do not inform about population-level dynamics.

Additionally, there are a large number of papers showing how current attitudes and behaviours of other people can influence someone to adopt or abandon a non-meat diet (Ruby and Heine, 2012; Hodson and Earle, 2018; Larsson et al., 2003; Cherry, 2015; Jabs et al., 2000; Jabs et al., 1998; Merriman, 2010; Almassi, 2011; Menzies and Sheeshka, 2012; Paisley et al., 2008; Yoo and Yoon, 2015; Beardsworth and Keil, 1991). These papers can help to explain the change in numbers of people following a non-meat diet between two points in time, but not dynamics over an extended period. However, together these papers show an important empirical point about dynamics in vegetarian and vegan rates. While many influences such as family, friends, and work and school colleagues are common across different countries, the extent to which they positively or negatively influence adoption is dependent on social context (Paisley et al, 2008; Beardsworth and Keil, 1991; Merriman, 2010). For example, dietary choice can be influenced by the occurrence and traditions of social events (Jabs et al., 1998; Yoo and Yoon, 2015), prevailing political attitudes (Hodson and Earle, 2018), and gender power balance (Merriman, 2010). Overall, country setting can be an important influence on the level and dynamics of vegetarian and vegan rates (Leahy et al., 2010; Yoo and Yoon, 2015).

In this paper, we formulate a flexible model of dietary choice, and use it to show how vegetarian and vegan rates in a population jointly change over time. We fit our model to a pseudo-panel of U.K. household data, and estimate it using panel vector autoregression estimators. Our estimates show that, in the U.K., the rate of vegetarianism is determined by the current characteristics of households, and not by the lagged rates of household vegetarianism and veganism. However, the rate of veganism is influenced by both current household characteristics, and by its own lagged value. We use our estimates to find equilibrium rates of vegetarian and vegan consumption, and show that the equilibrium is stable in that dietary dynamics are covariance-stationary, so that rates of consumption return to their equilibrium levels following a temporary event which changes them. We characterise campaigns promoting vegetarian and vegan diet adoption in terms of generalised impulse response functions, and use them to show that, in the U.K., a persistent vegetarian campaign significantly increases the proportion of people following a vegan diet.

We start by presenting our theoretical model, before describing the material and methods. Then we present the results, and our conclusions.

Model

A population has a large number of consumers indexed by *i* who in any time period *t* consume diet D_{it}. D_{it} may be one of three diets. The first diet is an omnivorous diet, in which meat is consumed. The second diet is a vegetarian diet, in which no meat is consumed but other animal products such as eggs and dairy are consumed. The third diet is a vegan diet, in which no animal products are consumed. It is plausible that a consumer may also identify with a "reducetarian" diet in which meat is limited but not removed (One Step for Animals, 2018), and their presence may alter the dynamics of vegetarian and vegan rates. We do not consider such diets in our main analysis, but in the conclusion we propose one way of including them in our model.

Consumer *i* derives utility from selecting a vegetarian diet at time *t*, which measures how much the consumer values it compared with the alternative diets when making a choice between them (Kahneman et al., 1997). This selection utility is analogous to food reward, representing the value of a food to an individual when assessing whether to eat it (Rogers and Hardman, 2015), and depends on various personal and social influences. One influence is that the consumer's utility depends on their own diet in the previous period. Change in consumers' preferences for meat consumption often takes a long time (Beardsworth and Keil, 1991), and may occur through a number of stages (McDonald, 2000; Lea et al., 2006; Wyker and Davison, 2010; Mendes, 2013). For example, someone may have to learn where to purchase new ingredients, and how to eat healthily under their new diet (McDonald, 2000). It can be psychologically and mentally demanding to make the shift, and someone may persist with their current diet in order to avoid the effort associated with it. They may also seek to maintain their consumption patterns in order to be consistent with their own past behaviour, which may help to support their self-esteem (Cialdini and Goldstein, 2004; Jabs et al., 2000). Additionally, if someone's diet has substantial elements in common with another sort of diet (for example, both omnivorous and vegetarian diet contain milk products), the extent to which someone has to change their consumption patterns to consume the other diet is reduced, and it may be easier to move between them than between diets with greater differences.

Another influence on the utility that a person derives from their diet is the diet recently chosen by their peer group (Ruby and Heine, 2012; Larsson et al., 2003; Cherry, 2015; Hodson and Earle, 2018; Merriman, 2010; Yoo and Yoon, 2015; Beardsworth and Keil, 1991). A peer group may encourage someone to consume a diet by direct communication with them (Merriman, 2010; Cherry, 2015; Yoo and Yoon, 2015) or by providing an example or norm for them to follow (Beardsworth and Keil, 1991; Cherry, 2015; Jabs et al., 2000; Yoo and Yoon, 2015). If other people already consume the diet, then a person may consider consumption to lead to approval by the group (Beardsworth and Keil, 1991; Cialdini and Goldstein, 2004; Jabs et al., 2000), increasing the utility associated with its selection. Further, when other people consume a diet, the merits and practicalities of the diet may become better known (McDonald, 2000). A person considering consumption therefore faces less uncertainty about the outcomes, and they may value consumption more highly as a result.

Thus, consumer *i* derives utility from selection of a vegetarian diet at time *t* equal to

$$U(D_{it} \mid D_{it} = vegetarian) = f(L_{it-1}, M_{it-1}, H_{it-1}, l_{it-1}, m_{it-1}, h_{it-1}, X_{it})$$

where L_{it} is an indicator variable equal to 1 if D_{it} is an omnivorous diet and 0 otherwise, M_{it} is an indicator variable for whether D_{it} is a vegetarian diet, and H_{it} is an indicator variable for whether D_{it} is a vegan diet. l_{it}, m_{it}, and h_{it} are the proportions of consumer *i*'s peer group who at time *t* are following an omnivorous diet, a vegetarian diet, and a vegan diet respectively. X_{it} is a vector of control variables. *f* is a real-valued function.

The utility that consumer *i* derives from an omnivorous diet and a vegan diet are similarly specified. Without loss of generality, we can write these utilities as functions without explicit dependence on L_{it-1} and l_{it-1}, since $L_{it-1} = 1 - \max(M_{it-1}, H_{it-1})$ and $l_{it-1} = 1 - m_{it-1} - h_{it-1}$.

Consumers choose between the different diets based on the utilities they derive from them. The mean μ_{Mit} of the vegetarian indicator M_{it} is assumed to be linear in the determinants of the vegetarian diet's utility and its alternatives' utilities:

$$\mu_{Mit} = a_0 + a_1 M_{it-1} + a_2 H_{it-1} + a_3 m_{it-1} + a_4 h_{it-1} + a_5 X_{it} \qquad \text{(Eq1)}$$

We can view this expression as a first-order approximation to a more complex function, with local validity. As we will later see that our data fluctuate in a relatively small domain, this approximation is reasonable. Similarly, H_{it} has a mean

$$\mu_{Hit} = b_0 + b_1 M_{it-1} + b_2 H_{it-1} + b_3 m_{it-1} + b_4 h_{it-1} + b_5 X_{it}.$$

The expected vegetarian proportion in the peer group for consumer *i* at time *t* is

$$E\left(\frac{\sum_{j\in G(i)} M_{jt}}{|G(i)|}\right)=\frac{\sum_{j\in G(i)} \mu_{Mjt}}{|G(i)|} \qquad \text{(Eq2)}$$

where E is the expectations operator, μ_{Mit} is the mean of M_{it}, $G(i)$ denotes the peer group for consumer i, and $|G(i)|$ denotes the size of $G(i)$. We assume that if someone is in another person's peer group, their peer groups are the same. Examples of such groups are people with the same age, or households in the same region, or the whole population. For such a peer group, the values of m_{it} and h_{it} are the same for all members.

Substituting the mean equation (Eq1) in equation (Eq2), and since m_{it} and h_{it} are the same for all members of a peer group, we can write the relation as

$$E(m_{it})=a_0+(a_1+a_3)m_{it-1}+(a_2+a_4)h_{it-1}+a_5x_{it} \qquad \text{(Eq3)}$$

where $x_{it} = \sum_{j\in G(i)} X_{jt}/|G(i)|$ are the averages of the control variables in the peer group.

Similarly,

$$E(h_{it})=b_0+(b_1+b_3)m_{it-1}+(b_2+b_4)h_{it-1}+b_5x_{it} \qquad \text{(Eq4).}$$

Overall company profits from selling food are assumed to be independent of the number of vegetarians and vegans. This assumption can be justified by noting that there are very few people who do not follow an omnivorous diet, so that their purchasing decisions will have very little influence on most food company profits. There may be a handful of foods marketed only to vegetarians and vegans whose prices are affected by their numbers, but the bulk of foods eaten even in vegetarian and vegan diets are consumed by almost all of the population. As overall company profits are independent of the number of vegetarians and vegans, average food prices are independent of them as well. Thus, we can take average food prices as exogenous determinants of m_{it} and h_{it}.

We define the equilibrium values to be the points at which the expected values of m_{it} and h_{it} in the next period are the same as the values in the current period, holding the control variables constant. These equilibrium values can be found by putting m_{it-1} and E(m_{it}) equal to m_{it}^{equil}, and h_{it-1} and E(h_{it}) equal to h_{it}^{equil}, and solving in m_{it}^{equil} and h_{it}^{equil}. We have

$$m_{it}^{equil} = \frac{(b_2 + b_4 - 1)(a_0 + a_5 x_{it}) - (a_2 + a_4)(b_0 + b_5 x_{it})}{(a_2 + a_4)(b_1 + b_3) - (a_1 + a_3 - 1)(b_2 + b_4 - 1)} \qquad \text{(Eq5)}$$

and

$$h_{it}^{equil} = \frac{(a_1 + a_3 - 1)(b_0 + b_5 x_{it}) - (b_1 + b_3)(a_0 + a_5 x_{it})}{(a_2 + a_4)(b_1 + b_3) - (a_1 + a_3 - 1)(b_2 + b_4 - 1)}. \qquad \text{(Eq6)}$$

Material and methods

Data

Our vegetarian and vegan data are constructed from three sets of annual surveys of consumption by British households: the Family Expenditure Survey from January 1992 to March 2001, its successor the Expenditure and Food Survey from April 2001 to December 2007, and then its successor the Living Costs and Food module of the Integrated Household Survey from January 2008 to December 2014. The surveys were designed and run by the UK Government's Office of National Statistics and Department for Environment, Food and Rural Affairs, and their predecessor bodies. The data were provided by the U.K. Data Archive.

We construct a pseudo-panel from the data. Each year, the surveys resampled households from a complete list of U.K. postal addresses, excluding a small number of addresses in remote areas. Thus, the data consist of a series of cross-section surveys. For the cohort dimension of our pseudo-panel, we group households according to the five year periods in which the survey respondent was born. These periods run from 1930-1934 to 1970-1974, giving nine cohorts, each corresponding to a peer group in our model. The cohorts were chosen in order to give at least 100 respondents in each panel period so as to ensure adequate convergence to panel means, which is necessary to avoid error-in-variables and identification issues (Cameron and Trivedi, p772; Baltagi, p212). The average number of respondents per cohort period is 537.

For the time dimension of the pseudo-panel, we use survey year. Data collection occurs throughout the year, and the data also contain the quarter in which the household was surveyed. The survey quarter is used in a pseudo-panel built by Banks et al. (2001) who also have a dynamic model and Family Expenditure Survey data. However, it is possible that the sequence in which households are surveyed during the year may change the pattern of influence between households in successive time periods – for example, if households surveyed in the first quarter have little social contact with households in the second quarter, the intertemporal influence of diet would appear to be lower. It would be difficult to separate this sequencing effect from the peer group effect proposed in our model. Thus, we take the survey year as the time dimension in our analysis. Although the time dimension of our panel is reduced by using years rather than quarters, our estimation method (least squares dummy variables with Kiviet correction) mitigates problems linked to moderate time dimension, as discussed in the statistical methods section.

Over the 1992-2014 period, the proportion of households initially contacted that completed the final survey varied between 50 to 70 percent of households. Although the response rates are quite high, from 1998 onwards the surveys provide weights to correct for possible non-response bias. Prior to that date, weights were not available, and to maintain comparability between the early and late data we do not use weights to generate our reported results. However, to ensure that our results are not overly influenced by non-response bias, we also ran estimates with the weighted data over the restricted sample. The weighted results were similar to the unweighted results over the same sample. Compared with the unweighted results over the full sample, the weighted results had lower significance consistent with the smaller sample size, and with the possible impact of increased bias from the smaller panel dimensions. Overall, non-response bias does not seem to have much influence on our estimates.

The surveys provide personal and demographic information about the households, as well as information on their expenditure. Adult members were asked to take part in an initial interview collecting information about the household, and its large or regular expenditure. They were additionally asked to complete a daily diary of their detailed expenditure over two weeks. From 1995 onwards, children were also requested to complete expenditure diaries. To ensure comparability over time, we only use expenditure data from adults. The processed data are available in accompanying online files for this paper.

Variables

The vegetarian rate is calculated as the proportion of households in a cohort that are following a vegetarian diet, expressed as a number from zero to one. A household follows a vegetarian diet if no individual within it bought meat but at least one individual did buy dairy or eggs. We do not consider a household's consumption of animal-derived products such as honey and gelatine, which are typically consumed in far smaller amounts than dairy or eggs and which are discussed much less often in critical commentary on animal rearing practices.

When calculating the rate, we exclude households that only consume convenience foods purchased as an entire meal rather than as its individual components. The main convenience foods within our data are take-away foods, meals bought and consumed in the workplace, and meals bought from restaurants and snack bars. The contents of these meals are not specified in the survey data, so we cannot distinguish whether they contain meat, dairy, or eggs (a similar issue arises in Leahy et al. (2010)).

We also considered excluding a much larger number of households that consumed some but not only convenience food, in case they were vegetarians or vegans at home but omnivores when eating out, and found results similar to those here but with lower significance. However, extensive exclusion brings its own problems. Firstly, it reduces sample sizes and so reduces estimate precision. Secondly, people who eat convenience foods are disproportionately from well-educated households with relatively few children in our sample, and such households are also disproportionately meat-avoiders (Hoek et al., 2004; Pohjolainen et al., 2015), so numbers of vegetarians and vegans would be underestimated. Thirdly, people often eat convenience food in the presence of other people outside their own household, so their exclusion may bias downwards the estimated impact of social interaction on consumption. Thus, we cannot fully correct for uncertainty arising from consumption of convenience foods, and we acknowledge it as a limitation of our paper.

We take households to be the consumers in our model, as in Vinnari et al. (2010). Individual purchases are reported in our datasets, but they may be made for others in the household so we can’t say that an individual is a vegetarian or vegan based on their purchases or absence of them. With household data, purchases are less likely to be made for a different unit and so are more likely to be an accurate reflection of behaviour. Household consumption data also avoid definitional problems where people often report themselves to be vegetarians despite consuming meat (Juan et al., 2015).

An alternative approach would be to calculate the number of people in each household who follow each type of diet, based on the consumption of the whole household. This approach is followed in Leahy et al. (2010). However, Leahy et al. (2010) have to use several stringent assumptions to calculate rates of individual vegetarian consumption. Moreover, in Leahy et al. (2010) the percentages of households following vegetarian diets do not differ markedly from the percentages of individuals following them, and nor do they differ substantially from the rates we find here (however Leahy et al. (2010) estimate that the number of vegan individuals in the U.K. is less than 0.05 of one percent over most of the period 1990-2006, which is lower than our estimates).

Our household rates are also similar to the individual vegetarian and vegan rates found in prior surveys (Vegetarian Society, 2018). In accompanying online files to this paper, we compare our average rates with rates from twenty five years of surveys sponsored by the U.K. Government, or undertaken by market research organisations, or in Leahy et al.'s (2010) study. For example, our paper finds average rates of vegetarian and vegan consumption in 2014 of 2.9 percent and 0.4 percent respectively, for households where the respondent was born between 1930 and 1974. In comparison for adults more generally, a 2014 British Social Attitudes survey finds rates of 5.9 percent and 0.2 percent, a 2016 Food Standards Agency survey finds rates of 3 percent and 1 percent, a 2016 Ipsos-MORI survey finds rates of 2.2 percent and 1.1 percent, and a 2017 Mintel survey finds rates of 3.9 percent and 1.0 percent.

The approximate similarity between household and individual rates may be expected. We identify two major factors which influence the difference between individual and household rates, and which work in different directions. On one hand, households that have any omnivores in them will be classified as omnivorous even if the other residents are vegetarian. This factor will tend to reduce the household vegetarian rate relative to the individual rate. On the other hand, vegetarians are more likely than omnivores to be in smaller households (Hoek et al., 2004; Pohjolainen et al., 2015). This factor will tend to increase the household vegetarian rate relative to the individual rate. The two factors appear to roughly cancel out, leaving our household rates similar to individual rates in earlier surveys.

As far as we are aware, our data provide the first national panel dataset on vegetarian and vegan rates, as well as being consistent with the rates found in the majority of other surveys.

The vegan rate is calculated as the proportion of households in a cohort that are following a vegan diet, expressed as a number from zero to one. A household follows a vegan diet if no individual within it consumed meat, dairy, or eggs.

As *control variables*, we used prior literature to guide our selection: the number of adults in the household (Hoek et al., 2004; Jabs et al., 2000; Merriman, 2010; Menzies and Sheeshka, 2012; Yoo and Yoon, 2015), the number of children (Vinnari et al., 2010; Pohjolainen et al., 2015), the proportion of residents who are female (Hoek et al., 2004; Merriman, 2010), a dummy for whether the reference person is married (Paisley et al., 2008), the average years of education for adults (Pohjolainen et al., 2015; Hoek et al., 2004), the proportion of resident adults who are employed (Hoek et al., 2004), and the gross normal weekly household income including allowances

(Hoek et al., 2004). All variables are calculated as averages in a cohort for each time period.

The control variables are highly correlated, so their full, separate inclusion will be likely to lead to biased estimates on their own and other coefficients. Procedures aimed at excluding some or all of the variables are very unreliable in the presence of high correlation (Olejnik et al., 2000), and may again lead to coefficient biases. In order to retain the full effect of these variables while avoiding collinearity, we ran a factor analysis with varimax rotation. We include three factors cumulatively accounting for over 99 percent of variance. We call these factors *established* (weighting most heavily on the number of children and employment status), *size* (weighting most heavily on the number of adults and married status), and *skills* (weighting most heavily on years of education and income).

We additionally considered inclusion of covariates measuring whether households are based in particular geographical regions, as U.K. food consumption shows some regional patterns (Morris and Northstone, 2015; Hawkesworth et al., 2017). However, much of the effect of region on food consumption acts through socio-economic factors (Hawkesworth et al., 2017), which we already control for in our data, and which are a more proximate cause. Region may not be additionally informative about vegetarian and vegan rates, and may cause collinearity. To check whether these considerations were correct, as an additional covariate we included the proportion of each cohort resident in eleven U.K. regions (with London taken as an omitted base reference). Although the overall pattern of results was not changed, we found that parameters lost significance individually and collectively, and the Akaike and Bayesian information criteria both preferred the model without the regional proportions, pointing to collinearity and possible irrelevance problems. Similar outcomes were obtained when we used proportions resident in each U.K. constituent country. We therefore do not include region as a covariate in our main results.

Time dummies control for price changes, as well as the effect of other shocks such as the BSE crisis that may simultaneously change both vegetarian and vegan rates.

Cohort dummies control for any influences that are constant within the cohort, such as social norms of meat consumption that were present in their childhood.

For comparison with earlier work, Table 1 summarises our original variables before cohort aggregation and factor analysis (at the start of the results section, we will summarise the aggregated and factorised variables entering the estimation). The significance stars on the means in the vegetarian and vegan columns denote significant differences from the means in the omnivorous column. Vegetarian and vegan households tend to be smaller, with a higher proportion of employed adults and more educated adult members (consistent with the findings in Hoek et al. (2004) and Pohjolainen et al. (2015)). Their reference person is married less often, and is younger. They also have a lower income, consistent with a smaller and younger household. Vegan households have a lower proportion of female residents.

	Omnivorous households	Vegetarian households	Vegan households	All households
Number of adults	1.82	1.46***	1.36***	1.81
	0.73	0.67	0.57	0.73
Number of children	0.60	0.39***	0.28***	0.59
	1.00	0.84	0.73	1.00
Proportion of females	0.53	0.52	0.45***	0.53
	0.30	0.40	0.41	0.30
Reference person married (dummy)	0.53	0.27***	0.19***	0.52
	0.50	0.44	0.40	0.50
Reference person age	51.66	46.01***	42.17***	51.45
	16.94	18.18	17.45	17.02
Average years of education	11.89	12.83***	12.79***	11.92
	2.52	3.11	3.09	2.55
Proportion of employed adults	0.54	0.57***	0.63***	0.54
	0.45	0.47	0.46	0.45
Weekly income	539.85	469.95***	486.43***	537.53
	498.54	467.01	551.78	498.09
N	138419 (96.6%)	4182 (2.9%)	761 (0.5%)	143362 (100%)

Table 1: Means and standard deviations for households using original variables, prior to cohort aggregation and factor analysis.

Notes: Standard deviations are reported below means. In the vegetarian and vegan columns, stars denote significant differences from the means in omnivorous households. * denotes ten percent significance, ** denotes five percent significance, and *** denotes one percent significance.

Statistical methods

We estimate the following empirical specification:

$$m_{it} = A_1 m_{it-1} + A_2 h_{it-1} + A_3 x_{it} + u_{m,i} + v_{m,it} \quad \text{(Eq7)}$$

$$h_{it} = B_1 m_{it-1} + B_2 h_{it-1} + B_3 x_{it} + u_{h,i} + v_{h,it} \quad \text{(Eq8)}$$

where $u_{m,i}$ and $u_{h,i}$ are time-invariant normal random variables, and the $v_{m,it}$ and $v_{h,it}$ are zero-mean, normal random variables. $v_{m,it}$ and $v_{h,it}$ may be correlated with each other contemporaneously.

The pair of equations (Eq7) and (Eq8) takes the form of a vector autoregression (VAR) for a panel dataset. By construction, every m_{it} (t = 1, 2, …) is correlated with the group random variable $u_{m,i}$, and so in equation (Eq7) the determinants m_{it-1} and $u_{m,i}$ are correlated. Similarly, in equation (Eq8) the determinants h_{it-1} and $u_{h,i}$ are correlated, and the correlations make a pooled OLS estimator of equations (Eq7) and (Eq8) inconsistent. There are various econometric methods for estimating the equations that are consistent for large panel dimensions, and have known order of bias for smaller panels. As the pseudo-panel data presented in the data section have moderate time dimension *T* and small cross-sectional dimension *N*, our main estimation method is least squares dummy variables (LSDV) with the Kiviet (1995) correction, which has been shown to have a small bias at these dimensions (Judson and Owen, 1999; Bun and Kiviet, 2003), and with equal or lower order of bias as a function of the panel and time dimensions than the main competing methods (Bun and Kiviet, 2006). We estimate equations (Eq7) and (Eq8) separately, and calculate the cross-equation error covariance matrix using the estimated errors.

We will also report results from several other methods for comparison. They are least squares dummy variables, pooled OLS, and panel VAR with forward orthogonal deviations (Love and Zicchino, 2006; Abrigo and Love, 2016). Our estimations were performed in STATA using the user-written commands xtlsdvc (by G.S.F. Bruno) and pvar (by M.R.M. Abrigo and I. Love). The code is available in accompanying online files for this paper.

Results

Summary statistics

Cohort	Cell size	Vegetarian rate (0 to 1)	Vegan rate (0 to 1)	Established	Size	Skills
1930	450	0.0174	0.0023	-1.34	-0.63	-0.89
	69	0.0098	0.0031	0.52	0.99	0.99
1935	432	0.0188	0.0032	-0.97	-0.03	-0.65
	73	0.0083	0.0033	0.66	0.77	0.67
1940	473	0.0199	0.0037	-0.57	0.53	-0.48
	53	0.0080	0.0035	0.70	0.74	0.39
1945	589	0.0222	0.0032	-0.20	0.79	-0.05
	65	0.0069	0.0029	0.61	0.57	0.42
1950	557	0.0229	0.0041	0.17	0.70	0.31
	69	0.0063	0.0026	0.59	0.39	0.60
1955	591	0.0279	0.0040	0.50	0.52	0.41
	87	0.0084	0.0027	0.70	0.54	0.86
1960	661	0.0304	0.0048	0.77	-0.01	0.41
	103	0.0052	0.0028	0.60	0.65	0.81
1965	619	0.0368	0.0081	0.90	-0.58	0.37
	93	0.0120	0.0037	0.35	0.68	0.79
1970	461	0.0521	0.0124	0.74	-1.30	0.58
	128	0.0168	0.0076	0.28	0.69	1.05
All	537	0.0276	0.0051	0.00	0.00	0.00
	115	0.0141	0.0048	0.95	0.95	0.91

Table 2: Means and standard deviations, by cohort, and calculated across periods.

Notes: Standard deviations are reported below means.

Variable means and standard deviations split by cohort are shown in table 2. Mean cell sizes exceed 400 for each cohort, where the means are calculated over time periods. Vegetarian and vegan rates tend to be higher for later cohorts. The control variables *established* and *skills* also tend to be higher for later cohorts, but the control variable *size* doesn't display a monotonic trend.

Figure 1 shows the vegetarian and vegan rates for our dataset. It presents the mean rates in each time period, averaged over households in all cohorts, in contrast to table 2, which presents mean rates in each cohort, averaged over all time periods. Vegetarian rates are the solid line, and fluctuate around 2.8 percent. They perhaps went into a trough around 2002, before trending upwards more recently, but the trend is unclear. Vegan rates are the dashed line, and fluctuate around 0.5 percent. No trend is discernable.

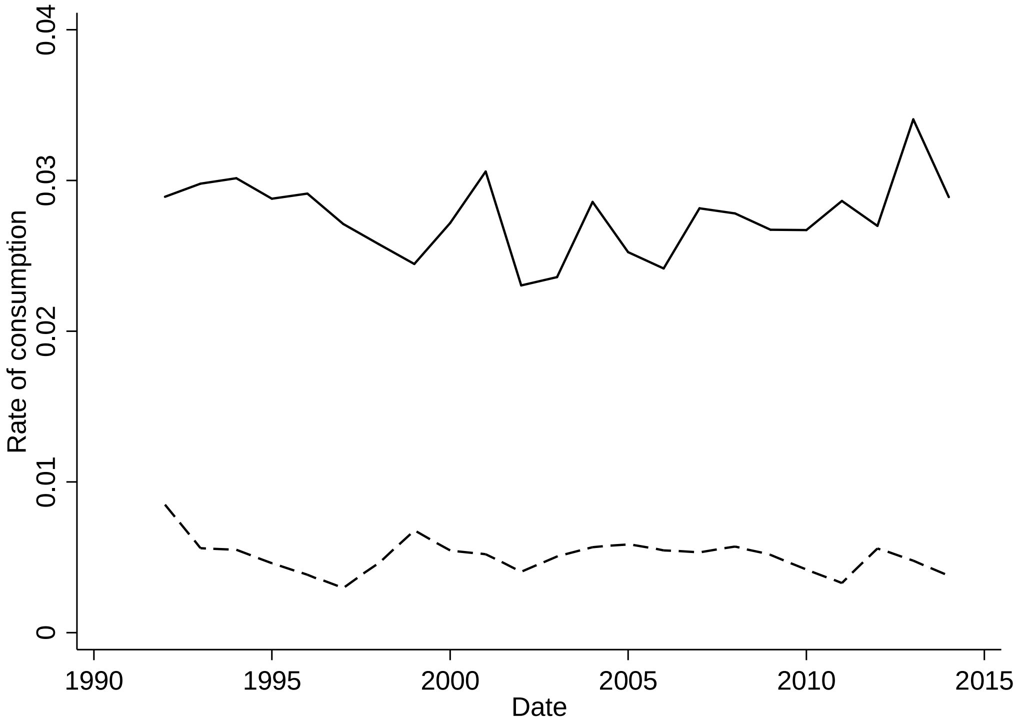

Figure 1. The rates of vegetarian (solid line) and vegan (dashed line) consumption among households that have a main survey respondent born from 1930 to 1974. Rates are proportions from zero to one.

Estimated coefficients

Table 3 presents our estimated coefficients. The diagnostic statistics indicate that the model and empirical specifications are reasonable. R^2 is moderate to high across all specifications indicating good explanatory power, and the Wald test *p*-values are close to zero, indicating that the coefficients are jointly significant. The ρ statistic measures cross-equation error correlation, and is low across all specifications indicating that there is little correlation between the error terms in the vegetarian and vegan equations. The *r* statistic measures error autocorrelation, and is low and at most marginally significant across all but one specification (namely, the vegan equation using the panel VAR) providing little reason to reject our dynamic specification.

The LSDV (Kiviet corrected) estimator in columns 1 and 2 is our preferred estimator. It has highest explanatory power among the estimators in terms of R^2 for both the vegetarian and vegan equations. We also prefer this estimator on the grounds that it has low bias at the dimensions of our panel, as explained in the statistical section. We further examine the estimator's fit graphically. In accompanying online files for this paper, we present graphs showing the fitted and observed values within each cohort over the survey period, for vegetarian and vegan rates. The fit is generally good.

In column 1, we see the results for the least squared dummy variables (Kiviet corrected) estimator, with the vegetarian rate as the dependent variable. The lagged vegetarian rate and lagged vegan rate have an insignificant effect on the vegetarian rate. The *established* and *size* variables have significantly negative effects, while the *skills* variable has a significantly positive effect. In column 2, the results are shown for the least squared dummy variables (Kiviet corrected) estimator, with the vegan rate as the dependent variable. The lagged vegetarian rate has a positive but insignificant effect on the vegan rate, while the lagged vegan rate has a significantly positive effect on the vegan rate. The *established* and *size* variables have significantly negative effects. The *skills* variable has an insignificant effect.

Columns 3 and 4 present the results for the least squares dummy variables estimator. The coefficients are similar to those of the LSDV (Kiviet corrected) estimator, with the exception of the coefficients on the lagged vegetarian variable in the model of vegetarian consumption in column 3 and the lagged vegan variable in the model of vegan consumption in column 4. These coefficients are lower than in the LSDV

(Kiviet corrected) estimator. The least squares dummy variables estimator has a downwards bias on the estimates of the coefficient on the lagged dependent variable (Nickell, 1981), so its estimate will tend to be lower than the actual coefficient (and the LSDV (Kiviet corrected) estimate, as we see in columns 1 and 2).

Columns 5 and 6 present the estimates for the pooled OLS estimator. The coefficients on the lagged vegetarian and vegan variables are much higher and more significant than in the LSDV (Kiviet corrected) estimator in both the model of vegetarian consumption in column 5 and the lagged vegan variable in the model of vegan consumption in column 6. Pooled OLS omits the cohort specific error components ($u_{m,i}$ and $u_{h,i}$ in equations (Eq7) and (Eq8)), so neglects the correlation between the error and lagged dependent variables. As a result, the estimator produces upwards biased estimates of these variables' effects, and its estimates will tend to be higher than the actual coefficients (as well as the LSDV (Kiviet corrected) estimates in columns 1 and 2).

Columns 7 and 8 present the results from a panel VAR estimator with forward orthogonal deviations described in Abrigo and Love (2016). The lagged vegetarian rate and lagged vegan rate have an insignificant effect on the vegetarian rate in column 7, while the lagged vegetarian rate has a positive but insignificant effect on the vegan rate and the lagged vegan rate has a significantly positive effect on the vegan rate in column 8. Both of these findings are similar to those in the LSDV (Kiviet corrected) estimator.

Method	LSDV (Kiviet corrected)		LSDV		Pooled OLS		Panel VAR	
Data	Pseudo-panel		Pseudo-panel		Pseudo-panel		Pseudo-panel	
Dependent variable	Vegetarian rate	Vegan rate	Vegetarian rate	Vegan rate	Vegetarian rate	Vegan rate	Vegetarian rate	Vegan rate
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Vegetarian rate (lag)	0.105	0.049	0.058	0.050*	0.304***	0.100***	0.083	0.066
	0.072	0.036	0.066	0.028	0.068	0.027	0.161	0.062
Vegan rate (lag)	0.082	0.254***	0.086	0.192***	0.552***	0.313***	0.079	0.337**
	0.202	0.082	0.164	0.071	0.176	0.070	0.401	0.168
Established	-1.247***	-0.239**	-1.277***	-0.248**	0.000	0.013	-1.294	-0.083
	0.218	0.103	0.227	0.098	0.132	0.053	1.097	0.438
Size	-0.537***	-0.095**	-0.569***	-0.110***	-0.467***	-0.087**	-0.547***	-0.108*
	0.114	0.053	0.093	0.040	0.089	0.035	0.153	0.061
Skills	0.344*	-0.022	0.345**	-0.031	0.596***	0.019	0.079	0.014
	0.178	0.077	0.171	0.073	0.188	0.075	0.428	0.192
Group dummies	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Time dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(Pseudo) R^2	0.74	0.58	0.74	0.58	0.68	0.55	0.40	0.26
Wald test *p*-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ρ (cross-equation error)	0.03		0.03		0.13		0.03	
t-test *p*-value (of $\rho = 0$)	0.63		0.63		0.06		0.70	
r (error autocorrelation)	-0.09	-0.10	-0.04	-0.04	-0.13	-0.13	-0.05	-0.16
t-test *p*-value (of $r = 0$)	0.24	0.17	0.61	0.60	0.08	0.08	0.48	0.02
N	198	198	198	198	198	198	189	189

Table 3. Estimates of the dynamic determinants of vegetarian and vegan diet consumption

Notes: Standard errors are shown below the estimated coefficients. * denotes ten percent significance, ** denotes five percent significance, and *** denotes one percent significance. Coefficients and standard errors on the *established*, *size*, and *skills* variables are multiplied by 100 for readability. Pseudo R^2s are calculated as the squared correlation between observed and predicted values including fixed effects. For the Panel VAR, the pseudo R^2 is calculated on the cohort- and time- demeaned values. LSDV is the least squares dummy variables, OLS is ordinary least squares, and VAR is vector autoregression.

The estimates in table 3, columns 1 and 2 can be used to calculate equilibrium rates of vegetarian and vegan consumption given the values of the determining variables in 2014. The equilibrium rates were defined in the model section to be the values at which the expected vegetarian and vegan rates in the next period are the same as the rates in the current period, holding the control variables constant and calculated using our estimated parameters. We use equations (Eq5) and (Eq6) to calculate equilibrium numbers of vegetarians and vegans within each cohort, and then aggregate across cohorts to find overall rates. The equilibrium vegetarian rate in 2014 was 2.84 percent, compared with an actual rate of 2.89 percent, while the equilibrium vegan rate was 0.48 percent compared with an actual rate of 0.38 percent[3]. Thus, the rates were close to their equilibrium values.

The equilibrium values change over time as the control variables change. Time dummies in the vegetarian equation show a drift downwards, which indicates a tendency for vegetarian rates to decline over time, while time dummies in the vegan equation show no significant drift. Fixed effects panel regressions of each control variable on a time trend show that the *established* variable has a negative time trend, the *size* variable has negative time trend, and the *skills* variable has a positive time trend (panel unit root tests reject unit roots as an alternative explanation for the drifts). From table 3, we see that these changes are likely to increase the equilibrium rates of vegetarian and vegan consumption among households.

We can classify the stability of the equilibrium by looking at the eigenvalues of the VAR system formed by the estimated coefficients in table 3, columns 1 and 2. The eigenvalues are less than one in absolute value (0.08 and 0.28), so the VAR process is covariance-stationary (Hamilton, 1994, p. 259). This means that the effects of a

[3] In calculating the vegan equilibrium, we use the average value of the estimated time dummies over the period 2010-2014, as the 2014 time dummy from equation (Eq8) is anomalously low by historical standards. If we use the 2014 time dummy, the equilibrium rate is 0.31 percent.

shock to the rates of vegetarianism or veganism (i.e. a temporary event changing those rates) will fall to zero over time, and the rates will tend to return to their equilibrium level. We discuss this issue further in the next section.

Vegetarian campaigns and vegan adoption

In this section, we will assess the claims that campaigns which promote vegetarian adoption do not promote vegan adoption (Dunayer, 2004, p.155; Francione, 2010). To do so, we start by arguing that the estimated relations in table 3 show causal relations from lagged vegetarian and vegan rates to current ones. We then argue that generalised impulse response functions show the effects of campaigns within cohorts, before calculating the effect of a vegetarian impulse on a vegan response, which allows us to see how vegetarian campaigns affect the vegan rate.

Table 3 plausibly shows the strength of the causal relation between the lagged vegetarian and vegan rates to current ones, for a number of reasons. Firstly, there is a believable theoretical rationale for suspecting a causal link: people find it easier to consume a diet if they already follow a diet which shares much of its content. Secondly, the relation expresses the strength of Granger causality between the variables – the statistical significance of the lagged variables' effect on current variables is shown. Thirdly, our model controls for household fixed effects and other potential influences which could be a common source of variation in both vegetarian and vegan rates. Fourthly, it is unlikely that large numbers of people switch to a vegetarian diet in anticipation of later vegan consumption (which would explain reverse causality from vegan consumption to lagged vegetarian consumption). People often consume a vegetarian diet as meritorious in itself (for example citing concerns over health or factory farming as in Shephard (2015)), and vegan advocacy often recommends either a complete break from animal product consumption or consists of distinct messages promoting meat avoidance and milk avoidance, rather than promoting an explicit staged adoption.

Given our causal interpretation, the generalised impulse response function (GIRF) (Pesaran and Shin, 1998) from a vegetarian impulse to a vegan response can be interpreted as showing how a temporary campaign promoting vegetarian adoption within a cohort affects vegan adoption. The GIRF assumes that there is an initial shock to the error term $v_{m,it}$ in equation (Eq7), which increases the vegetarian rate within a cohort. The GIRF then calculates the change in the vegan rate acting both through the error term $v_{h,it}$ in equation (Eq8) which is correlated with the shock term $v_{m,it}$, and through the dynamics of the panel VAR estimated in equations (Eq7) and (Eq8). The initial shock to the error $v_{m,it}$ in equation (Eq7) represents the temporary campaign promoting vegetarian adoption, while the correlated error $v_{h,it}$ in equation (Eq8) represents the initial effect of the campaign on vegan adoption. The dynamics in equations (Eq7) and (Eq8) represent the effect of the campaign as the effect changes over time – which is reasonable as we have just argued that the dynamics plausibly represent a causal relation between lagged and current variables. The GIRF thus allows us to see how the vegan rate changes immediately after the campaign, and at future times as well.

An alternative characterisation of a campaign is as a temporary change to one of the parameters in the model. For example, if we wanted to model a campaign in which vegetarians were encouraged in their diet, the a_1 parameter in equation (Eq1) may be temporarily increased, indicating that people are more likely to persist in their vegetarianism at the time of the campaign. From equations (Eq3) and (Eq4) we can see that the expected vegetarian rate would temporarily rise, but the expected vegan rate would stay the same. By comparison, with our characterisation of campaigns as a shock to the error term, the vegetarian rate would temporarily change, and the vegan rate would also temporarily change at the same time, because past data show that the changes are correlated with each other. The difference between the two campaign characterisations is analogous to the difference between impulse response functions and orthogonalised or generalised impulse response functions in time series analysis (Hamilton, 1994, p. 318-322; Pesaran and Shin, 1998). In practice, as the cross-equation error correlations in Table 3 are low, there will not be much difference in estimated campaign effects between the two characterisations.

Figure 2 presents the generalised impulse response function for a vegan response to a vegetarian impulse. We calculate the function using the parameter estimates from table 3, columns 1 and 2, and show the vegan response as a fraction of the initial vegetarian impulse. The size of the initial impulse following various campaigns has been examined in a number of studies, but is still subject to large uncertainties even for specific types of campaigns such as leafleting (Animal Charity Evaluators, 2017; Peacock and Sethu, 2017); for example, one study found that a leafleting campaign initially increased the combined vegetarian and vegan rate by 14 percent as a high estimate and one percent as a more conservative estimate (Animal Charity Evaluators, 2018). Thus, while our results indicate relative response size, the actual response size will depend on the uncertain initial campaign effect.

Figure 2 shows that at the time of the initial campaign promoting vegetarian adoption within a cohort, there is no significant change in the vegan rate, reflecting the low cross-equation error correlation. After one year, the increase in the vegan rate is equal to 0.05 of the initial increase in the vegetarian rate, and is marginally insignificant ($p = 0.101$). After two years, the increase in the vegan rate is equal to

0.02 of the initial increase in the vegetarian rate (and 99 percent significant), while after three years it is only 0.01 of the initial increase in the vegetarian rate. Thus, the effect of a vegetarian campaign on the vegan rate is highest after one year, and significant but small after two years. The vegan rate change declines to close to zero after three years.

We can also use the GIRF to see the effect of a persistent campaign that achieves the same initial increase in the vegetarian rate within a cohort at the start of every year. The effect on vegan adoption can be calculated by summing the GIRF responses over every time period. The cumulative increase in the vegan rate is equal to 0.09 of the initial increase in the vegetarian rate, with ten percent significance.

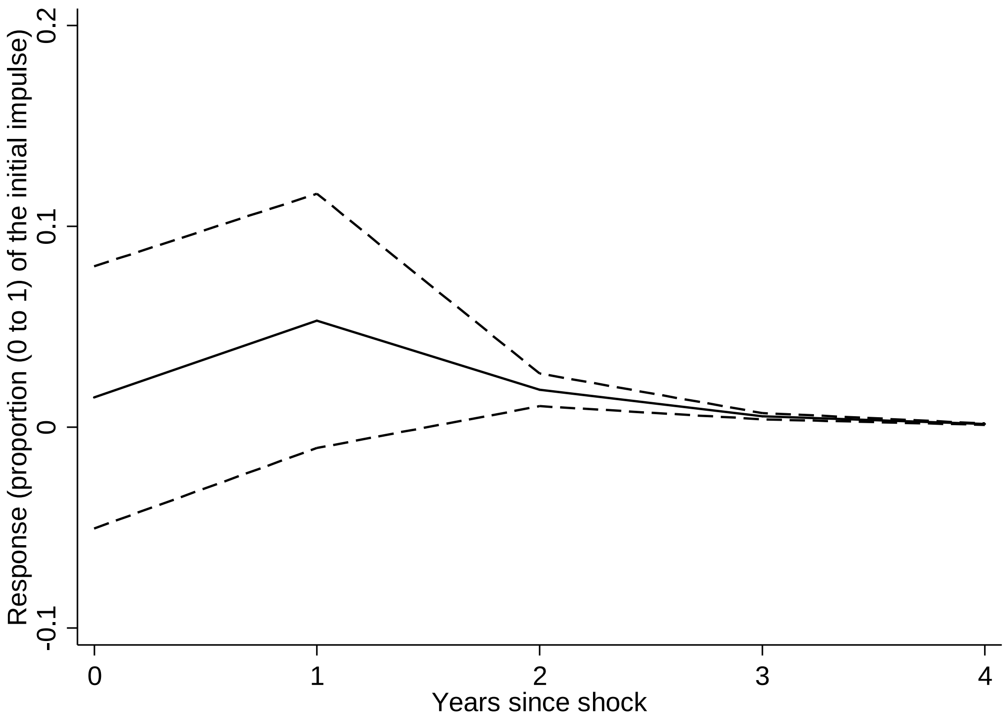

Figure 2. The generalised impulse response function for a vegan response to a vegetarian impulse within a cohort, with 95 percent confidence intervals.

Notes: The response is calculated from the least squares dummy variables (Kiviet corrected) estimates. The size of the vegan response is rescaled to be a fraction (zero to one) of the initial vegetarian impulse. The solid line shows the response, and the dotted lines show symmetric 95 percent confidence intervals. Standard errors at each time period are calculated from 1000 bootstraps.

Discussion and conclusion

This paper has examined the dynamics of the rates of vegetarianism and veganism in a population. We presented a flexible model of consumer dietary choice, and derived the joint dynamics of vegetarian and vegan rates at the population level. We fitted the model to a pseudo-panel of U.K. households based on 23 years of data, and estimated it using various panel vector autoregression methods. We used our model to estimate equilibrium vegetarian and vegan rates, and examined changes in rates after a shock. We demonstrated that the effects of campaigns promoting a vegetarian or vegan diet can be assessed using generalised impulse response functions, and examined how vegetarian campaigns affect the vegan rate, answering an active question among campaigners.

Our paper has made a number of contributions. We are the first authors to derive the joint dynamics of vegetarian and vegan rates in a population, supplementing earlier works looking at trends or interactions in omnivorous, vegetarian, and vegan consumption (Beardsworth and Bryman, 2004; Leahy et al., 2010; Vinnari et al., 2010). We fitted our model to a new U.K. dataset of aggregate vegetarian and vegan consumption that, as far as we are aware, is the first national panel dataset of vegetarian and vegan rates. For the U.K., we showed that the vegetarian rate is largely determined by current household characteristics, but that the vegan rate is determined both by current household characteristics and its own lagged value.

We also are the first authors to establish the existence and nature of the equilibrium rates of vegetarianism and veganism in the U.K. We found the equilibrium rates to be 2.84 percent for vegetarianism and 0.48 percent for veganism among households where the main survey respondent was born between 1930 and 1974, holding household characteristics constant. We showed that the equilibrium is stable, so that rates tend to return to it after a shock, and we also showed that the equilibrium rates have tended to increase over time as exogenous household characteristics change.

We have also contributed to the active debate on whether campaigns promoting a vegetarian diet also promote a vegan diet (Shephard, 2015; Dunayer, 2004, p.155; Francione, 2010). We are the first to demonstrate that the generalised impulse response function can be used to estimate temporary and persistent campaign effects, finding that in the U.K. a temporary vegetarian campaign causes an increase in the vegan rate after one year, equalling 0.05 of the initial increase in the vegetarian rate, but that the effect declines to close to zero after three years. We also found that for a persistent vegetarian campaign, the increase in the vegan rate is significant and equal to 0.09 of the initial increase in the vegetarian rate.

There are a number of directions for future research. The theoretical model could be revised to look at adoption dynamics within households, rather than between households as in this paper. There may be different mechanisms determining adoption within households, such as the influence of children or difficulties at holiday gatherings (Pohjolainen et al., 2015; Jabs et al., 1998). Another way to proceed would be to look at the extent of meat and dairy use, and the effect on them of campaigns, perhaps in a bivariate or trivariate model of consumption. Some animal advocates call for meat reduction to be a campaign target (Fischer and McWilliams, 2015; One Step for Animals, 2018), and researchers could use this model in conjunction with data on animal product use to investigate how vegetarian, vegan, and reduced-meat consumption interact.

Empirically, our model could be tested on a true panel of personal or household consumption instead of a pseudo-panel, although we are unsure if there are any existing panels which provide sufficient detail on both consumption and personal characteristics. Also, we could allow for the animal products consumed within convenience foods when calculating vegetarian and vegan rates, which would give us a more precise measure of vegetarian and vegan rates. Data limitations in the present paper meant that we did not know the content of convenience foods, and so we partially excluded them when calculating vegetarian and vegan rates. Again, we are unsure if there are any existing datasets providing sufficient detail for calculation.

Additionally, we could further integrate the population-level dynamics with results derived from individual-level data on vegetarian and vegan adoption, particularly as they relate to the influence of other people and campaigns (for example, at Humane League Labs (2018)). Individual data may give more detail than population-level data, but can less easily capture the secondary effects of influence whereby an influenced person then influences other people, so the two data types and their consequent analyses are complementary. Further, we could examine the model in other countries, with the dynamics of vegetarian and vegan rates likely to vary by country due to their traditions, political attitudes, and interpersonal power relations, as we noted in the introduction. For instance, collectivist and individualist countries may produce different dynamics, with individuals in collectivist countries perhaps less influenced by their own past personal choice and more influenced by past group choice (Yoo and Yoon, 2015).

In conclusion, this paper has introduced the first model describing the joint dynamics of vegetarian and vegan rates in a population. The model allows us to answer questions which are central to the promotion of these diets, and which can only be partially answered with previous approaches. In particular, the model allows for analysis of population-level interactions which are largely neglected in previous research. It is informative about the influences on dietary choices made already by hundreds of millions of people, and future changes in the number of people who will adopt a vegetarian or vegan diet.

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