Modelling adoption of meat-reduced diets using cellular automata, in the context of the climate and ecological emergency

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1 Summary

Many studies identify the climate and ecological emergency (C&EE) as amongst the top motivators for meat reduction in westerners' diets. Evidence from a smaller number of studies show familial and friendship influences to be equally or more important, but none have attempted to model this effect using agent-based techniques. This study will implement a cellular automata (CA) on a social network graph to model the adoption of dietary change, with agents' decisions based on both local and global influences. The goals are: to determine how model parameters influence the likelihood of "avalanche" effects, to inform policy, and to create a framework for future study.

2 Introduction

Food systems are responsible for 30% of anthropogenic GHG emissions, 70% of freshwater use, and 40% of land use (Willet et al., 2019). Livestock contributes a large part of this footprint with the majority of farmed land being used to grow feed (FAO, 2012). At sea, all but 10% of fisheries are overfished (Willet et al., 2019). In response to the C&EE, many are considering changes to their diets, either becoming vegetarian, vegan, or simply reducing their meat intake (Ploll et al., 2020). Societal norms and interactions can help or

hinder these transitions, with the behaviour of close friends and immediate family a key enabler (Hielkema & Lund, 2021).

Cellular automata (CA) are agent-based computational models composed of a large number of cells (or “automata”) each with a state and defined “neighbourhood”. At every time step, each automaton’s state is updated by a rule based on the state of neighbouring automatons. This makes CA ideal for simulating systems such as the diffusion of human behaviours, in which the next state of each agent is influenced by the current state of its peers.

Conway’s Game of Life is an early example of CA, designed to explore the simplest physics able to support life-like behaviour (Gardner, 1970). Figure 1 illustrates some simple GoL sequences. However, GoL can also exhibit highly complex behaviour. In fact, since it is Turing Complete (Rendell, 2011), it is able to simulate any system, however complex.

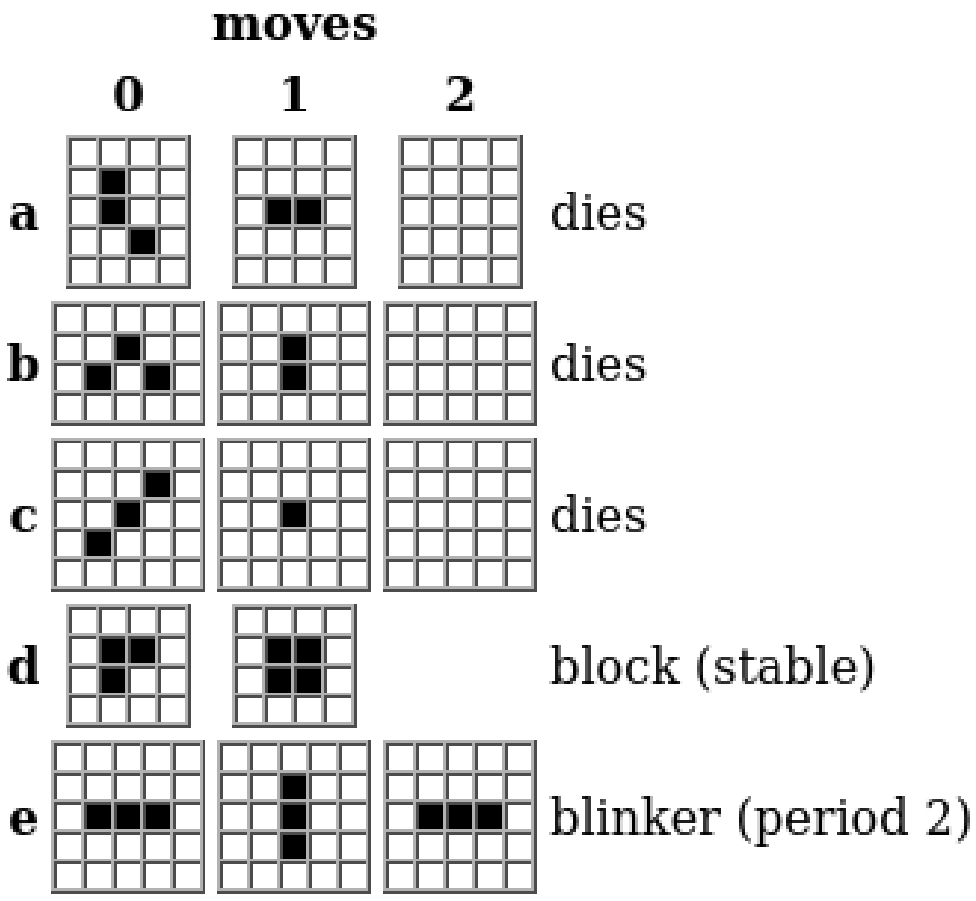

Figure 1: From Gardner (1970) - 3 generations of GoL from 5 alternative starting points. Neighbourhoods are 9-cell squares, states are absent (white) or present (black), and the rules are: 3 neighbours lead to cell-birth; 2 or 3 to cell-survival; and any other number to cell-death. More complex initial states generate apparently life-like behaviours.

GoL is deterministic and geometric (the cells being arranged in a 2D array). However, probabilistic and graph based CAs also exist, providing a framework for exploration of the dynamics of socially-influenced behavioural change.

3 Justification and Literature Review

In 2015, signatories at COP21 agreed to “limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels”. Six years later the IPCC identified that the remaining “1.5C carbon budget” was likely to be in the range 300-900 $GTCO_2$ (IPCC, 2021). For context, the central estimate of $450GTCO_2$ will be exceeded in just 13 years, if emission rates remain unchanged. Agriculture is a major contributor, responsible for 30% of current emissions, with meat production directly or indirectly responsible for the majority of those, in as well as other GHGs (FAO, 2012). In addition to climate, meat production negatively impacts ecosystems by requiring vastly more land per food-calorie produced. In summary, our desire for meat significantly contributes towards the crossing of two of nine planetary boundaries (Rockström et al., 2009). This justifies an exploration of factors that might facilitate the reduction of consumption levels.

Within the context of the C&EE proposed solutions fall into two categories: system level (or supply side) and individual responsibility (or demand side). An example of the former are the international agreements previously referred to which, if implemented, would likely see the price of emissions-intensive products such as meat rise. The latter is typified by the “Carbon Footprint Calculator”, introduced by BP (2004), which aims to nudge consumers into a lower emissions lifestyles. There is an active debate as to whether demand-led changes can feasibly impact widespread human behaviour. In fact, some commentators have claimed BP’s “Carbon Footprint” concept was introduced cynically in the belief that it would not reduce emissions. This theme is discussed by Baylor Johnson (2003) who invokes the “tragedy of the commons”, arguing that calls for individual action detract from the system changes necessary. In response Marion Hourdequin (2011) counters that the desire to follow social norms may see an individual-led revolution sweep through society. Both authors invoke game theory to justify their conclusions but neither attempt to build a model to test their claims.

A number of theories of individual change in the context meat-consumption are discussed in the literature. Ploll et al. (2020) look at the diffusion of vegetarian and vegan diets in Austria through a social innovation perspective, i.e. as a bottom-up social movement framed as a solution to a problem. Hodson and Earle (2018) consider political ideology as a predictor of lapses from vegetarian and vegan diets. The survey of attitudes towards meat-reduction in Denmark (Hielkema and Lund, 2019) adopts the transtheoretical model in which individuals pass through stages of change when modifying behaviour. Although they do not discuss modelling, Hielkema and Lund provide useful information for building a model. Firstly, the extent to which meat reduction is influenced by peer behaviour is quantified, and secondly their use of early transtheoretical states, such as “intention to reduce” and “meat reducer”, are shown to capture more of the picture than the simpler omnivore/vegetarian/vegan categories, which miss out the areas in which most of the action happens. All the above studies chart the extent to which demographics (e.g. gender, conservatism) and personal beliefs (towards the environment, animal welfare, and health), predispose a person towards a meat-reduced diet, lowering the convenience and peer-influence thresholds at which a change occurs. No study was found that took an interdisciplinary approach of computer modelling the diffusion of meat reduced diets, although the concept of simulation in the broader context of sociology has been discussed (Halpin, 1999).

The survey by Hielkema and Lund (2019) shows peer-influence and climate awareness to be the most important factors in individual's decisions to consider or adopt a meat-reduced diet. This makes agent-based simulation such as cellular automata an ideal lens through which to study the problem. Although, other factors are almost as important they can be considered fixed and modelled by making the automata demographics match those of a real population. Only peer-state and a global "climate-awareness" factors need to be modelled as variables.

There are multiple types of cellular automata based on geometric arrays, such as classic (deterministic) CA, and Probabilistic CA (Griffeath, 2015). Figure 2 shows a PCA in which states represent one of two voting intentions (Democrat or Republican) and the update rule reflects influence by local peers.

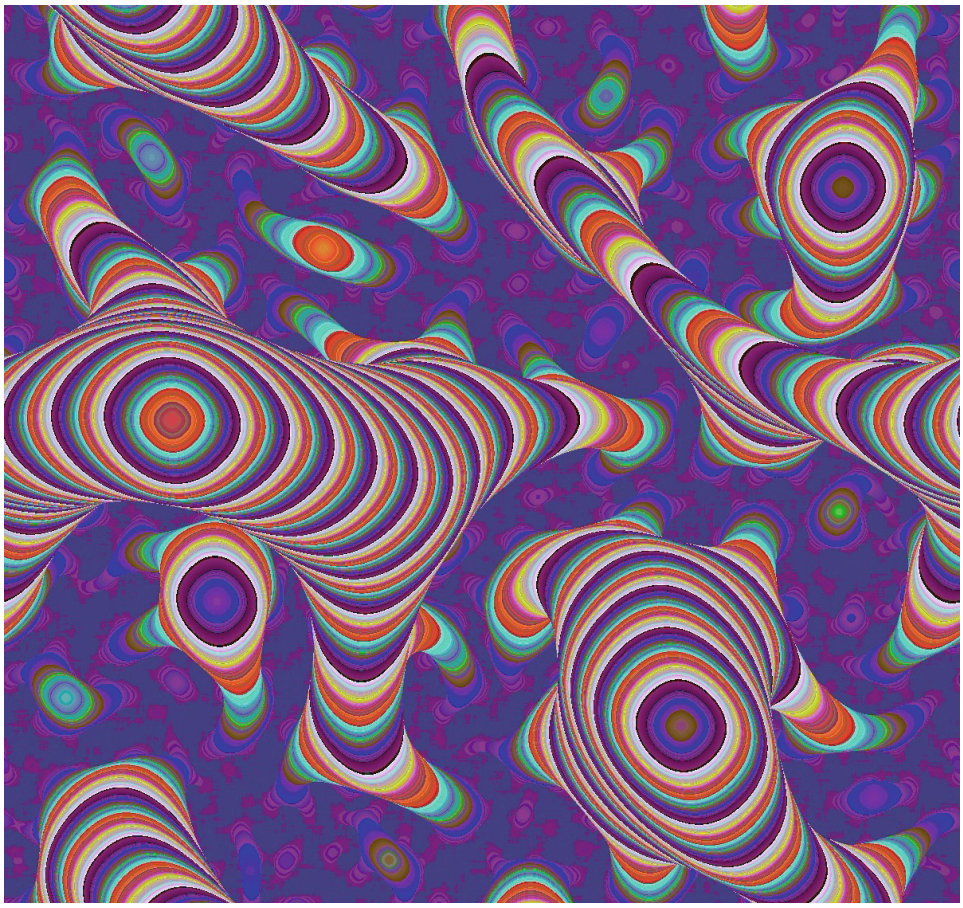

Figure 2: Adapted from Griffeath (2015), a PCA showing how a randomized population of Democrat and Republican voters converge towards a consensus given an update rule in which each cell switches allegiance to that of the majority of peers in its 21x21 cell neighbourhood. The colours indicate the generation in which the switch occurred.

The illustration shows that PCA are capable of simulating the type of non-linear phenomena, not amenable to normal mathematical techniques, that is required by this study. However the 2D arrays used by most classic CAs are not representative of real human social ties.

The classical grid array domain was replaced with nodal graphs in a study of relation-based Graph CAs (Małecki, 2017). Such "r-GCAs" provide an ideal framework for considering the diffusion of peer-influenced human behaviour, as one's peers are not simply those people who are geometrically closest. However, there is a debate over the best type of graph to use to represent social ties. Barabäsi et al. (2000) found WWW hyperlinks to be a Scale Free Network (SFN), in which the probability of having n links is proportional to $n^{-\gamma}$ for some constant $2 < \gamma < 3$ (web page linking is a form of social network). However, others have argued that SFNs are rare in real social networks (Broido & Clauset, 2019). An alternative that is widely used is the Small World Network (SWN) in which most links are geographically-local and there are a smaller number of long distance links (Huang et al., 2005). SWNs have average path lengths proportional to the log of the number of nodes in the network, a feature of real human networks as evidenced by the saying that "six handshakes" link any two humans alive. The truth is probably that the model needed depends on the context, and a graph for describing social media links may look very different to one that only includes the sort of peers that might influence a dietary change. In their study of urban disease outbreaks, Eubank et al. (2004) found the contact network to be similar to a SWN, and it may be that this provides a reasonable basis for using SWN in this study, since it is likely that only a small number of ties, who come into frequent physical contact, influence changes in a person's diet.

4 Overall Objective and Specific Goals

The overall objective is to determine the plausibility of widespread adoption of meat-reduced diets, as a result of peer-influence, and landscape factors such as raised climate-awareness or improved labelling. This can be broken down into specific goals

- Software implementation of a social network graph realistically representing strong and weak ties in a sample population, corresponding to the categories used by Hielkema and Lund (2021).
- Mathematical formulation of a CA model.
- Software design including runtime and memory estimates.
- Determination from literature of reasonable parameter values. These will control how peer states and landscape (i.e. global) factors affect the likelihood of one agent changing state over one time step.
- Software implementation of Bayesian CA model.
- Statistical analysis of the sensitivity of the CA model to parameters settings.
- Visualizations of model behaviour.
- Stretch goal: Extended model including shop and food-outlet automata, and corresponding sensitivity analysis.

5 Data and Methods

5.1 Programming Environment

`Python` and the `numpy` package will be used for efficient implementation of the model. Visualizations will be coded using the `matplotlib`, and `networkx` packages. If investigation indicates a link between model parameters and emergent phenomena such as “avalanche” effects, these will be studied quantitatively using `Rstudio`.

5.2 Initial Model Parameters

The purpose of the model is *not* to accurately make predictions about a real-life population; it is to create a new tool for understanding how reduced-meat diets may diffuse through society in the context of the climate and ecological emergency. In particular, it is intended to be used to evaluate the possibility of emergent phenomenon such as “avalanche” effects, where change spreads rapidly encompassing a large proportion of the population. Such a tool has the potential to aid understanding by social scientists and policy-makers. However, although it is unreasonable to expect accurate predictions from such a model, it is important that the most significant drivers are included, and that their causative strengths are correct to within an order of magnitude, otherwise the effects observed are unlikely to be representative of any real population.

This study will use data collected by Hielkema and Lund (2021) in which a random stratified sample of 1005 Danes were surveyed to determine current diets, as well as their intentions and motivations (or lack thereof) for reducing meat consumption. Their results suggest climate awareness and peer behaviour are the most significant factors in decisions to reduce meat consumption. Based on their paper, the model will initially use the parameters in Table 1.

Table 1: Initial parameters used in model

Parameter	Value	Comment
Time step	6 months	Following the transtheoretical model, respondents were asked about their intention to reduce “in the next 6 months”
States	“No intention”, “Intention”, “Meat reducer”	Hielkema and Lund report how the likelihood of being in each of these categories is influenced by neighbours and by global factors
Transition probabilities	To be inferred from paper	The probabilities are not presented directly by the authors, but may be extracted using mathematical techniques.
Initial states	“No intention”: 57.3% “Intention”: 11.4% “Meat reducer”: 31.2%	Directly reported by study
Landscape properties	To be inferred from paper	Global factors influencing the likelihood of transitioning between states, such as a televised campaign or a climate-related disaster

5.3 Social network graph

A key component of the model will be a realistic space in which the simulation proceeds. The model will use a graph in which vertices represent individuals and directed edges influential relationships. Edges will be weighted with one of two values, because Hielkema and Lund distinguish only between strong and weak ties, with strong interpreted as cohabitation.

A strong-tie social graph with bi-directional edges will be constructed using data from statistica.com (2021) for Danish household sizes. This graph will be randomly augmented with weak-tie edges using a statistical model derived from a literature search, and possibly based on either Small World or Scale Free models (see Figure 3).

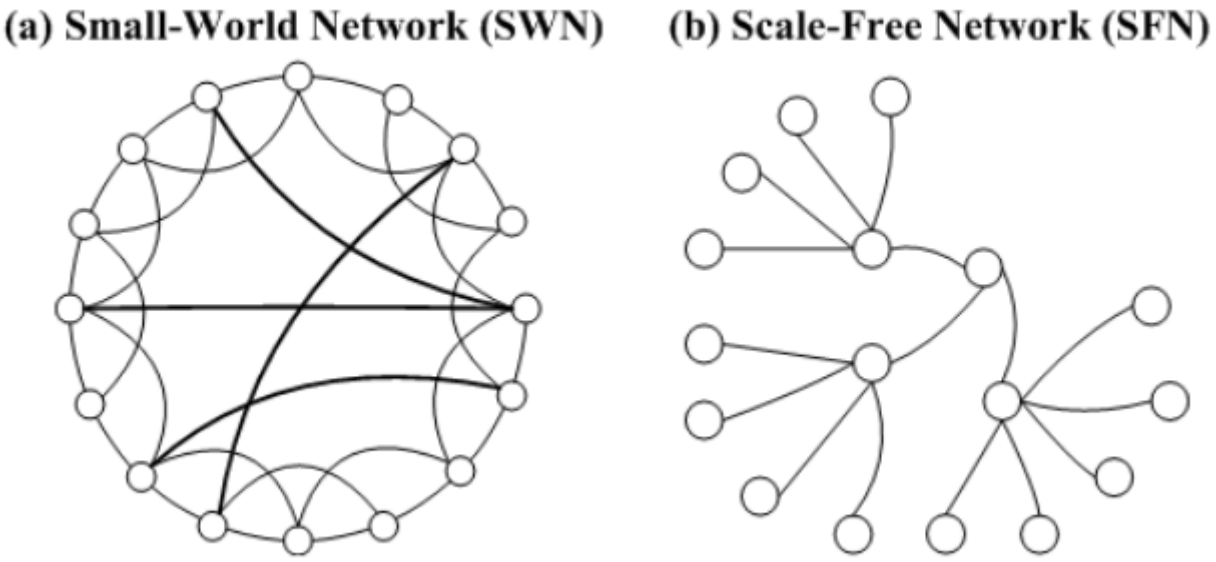

Figure 3: Options for simulating the graph of social ties, adapted from Huang et al. (2005). SWNs are characterised by a majority of geographically-local links with a minority of long-range links, and an average path length $\propto log(N)$*. SFNs are characterized by a probabilistic power law* $Pr(n \text{ peers}) \propto n^{-\gamma}$ *where* $2 < \gamma < 3$*.*

5.4 Stretch goal methods

If time allows, additional non-person nodes will be added to represent food outlets and shops. Connectivity will be local and based on research relating to typical catchment areas. A new set of states and interaction transition probabilities will be derived via literature search.

6 Potential Problems and Contingency Plans

There is a potential that the complexity of the model will be such that implementation and bug fixing take up more time than is available. For this reason the task has been split into an intermediate and a stretch goal. The intermediate goal will involve only agents representing individuals and the stretch goal will include businesses as well. The model should run in a reasonable time if the time and memory requirement analysis is performed correctly at the design stage. However, there is an option to port the implementation to `cython` (compiled `python`) in the case that the model runs too slowly for any meaningful analysis of it's behaviour. If the Scale Free Network model is chosen there may be difficulties creating a useful visualization. If this happens there is an option to adopt the Small World Network instead, which will be easier to represent inasmuch as the majority of connections are local.

7 Schedule

A Gantt chart detailing the proposed schedule can be found in Figure 4. Writing up is shown in grey and will take place in parallel with the research, design, coding, and analysis. Some time at the end is reserved for editing the final draft.

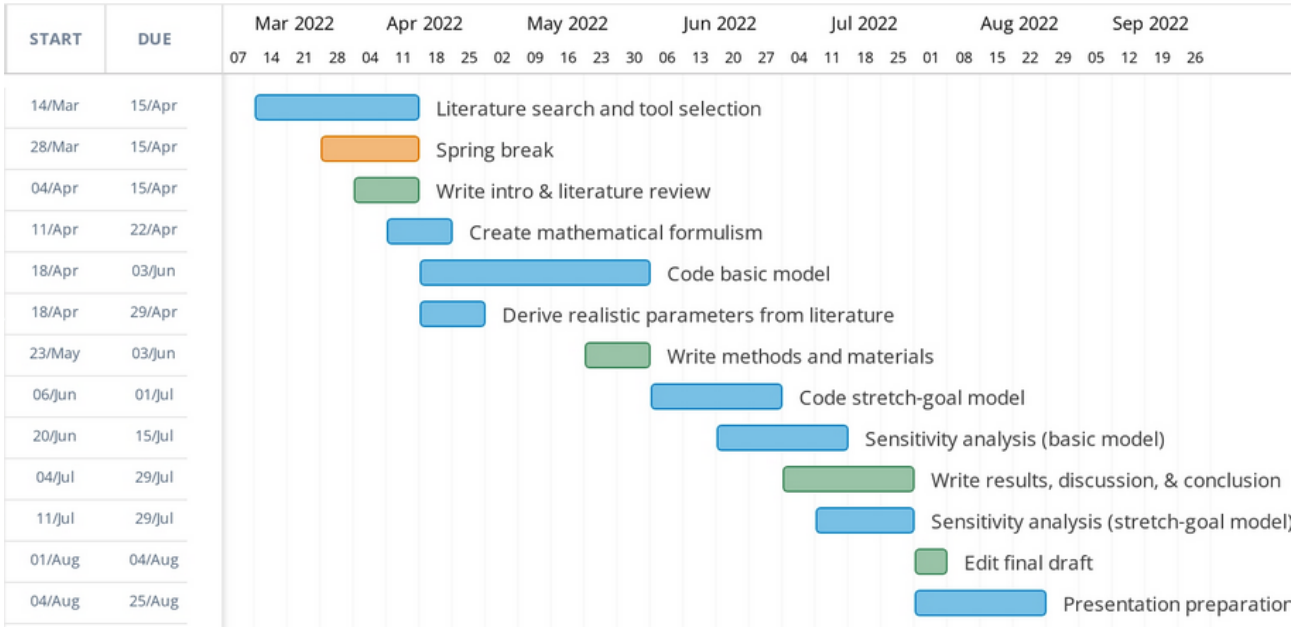

Figure 4: Work schedule for dissertation

8 Outcome

The intention is to provide a new perspective for understanding individual responses to the C&EE, and to determine whether rapid society-wide changes, driven by peer-pressure and landscape effects, are possible. This perspective could also be used to understand related behavioural changes, such as reduced fashion consumption, increased recycling, or EV purchase.

If avalanche effects are found, a parameter sensitivity analysis should provide information helpful to policymakers and campaigners; If they are not observed, this will provide evidence that attempts to reduce society's environmental footprint by appeals to individual responsibility alone, and in the absence of transformative system change, are flawed.

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