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Socio-ecological contagion in Veganville

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Research Article

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Abstract

In order to meet the 2015 Paris Agreement for 1.5°C global warming, per capita emissions need to come down to 2.9 tonnes by 2030. Food systems are known to be a significant source of an individual's carbon footprint and demands attention in sustainability management. The objective of this research is to conceptualise and define an intersection between contagion theory and socio-ecological systems models. This is achieved using a population dynamics model between two groups characterised by a distinct food regime: omnivores and vegans. The greenhouse gas emissions of each food regime is used to estimate the city's changing carbon foodprint as the food regimes shift by social contagion. Social contagion is identified as a catalyst for social tipping points, and emission pathways are explored with a variety of different contagion variables to test sensitivity towards a tipping point. The main finding is that the urban carbon foodprint can be reduced significantly with widespread adoption of veganism, but that the foodprint reaches a minimum at 1.97 tonnes CO_2-equivalent per capita. This demonstrates the need to embed food demand in urban climate governance such as nudging towards plant-based food alternatives. Nudging is discussed as a lever of ecological importance to social contagion. Lastly, socio-ecological contagion is defined as *the interactions between social contagion and damage done to ecological systems to measure peer-to-peer spread of environmental stewardship agendas*, such as the journey to Veganville.

Introduction

In 2015, the year the Paris Agreement was ratified, the world emitted an estimated 47 billion tonnes of carbon dioxide equivalents (WRI, 2021). This equated to approximately 6.4 tonnes per capita. Meeting the Paris Agreement's 1.5°C requires that we limit emissions to approximately 25 Gt CO_2-equivalent per year by 2030 (Rogelj et al., 2018). Based on population projections this will require per capita emissions to come down to 2.9 tonnes by 2030 (United Nations, 2019). Society's relationship with nature is under immense stress to meet this target, and turning the trajectory downwards requires a change in global behaviours constituting a social tipping point.

The concept of tipping points is well known from system theory. Tipping points are particularly relevant in socio-ecological systems (SES), which are the set of interconnected and interdependent social and ecological elements (Costanza, 2014). A *social* tipping point is observed when: *"within an SES at which a small quantitative change inevitably triggers a non-linear change in the social component of the SES, driven by self-reinforcing positive-feedback mechanisms, that inevitably and often irreversibly lead to a qualitatively different state of the social system." (Milkoreit et al., 2018).* Global concern over climate change has brought a rise in applications to influencing the trajectory of greenhouse gas emissions (GHGs) (Moser & Dilling, 2007; Otto, 2020).

Triggering a social tipping point can be achieved by collective action of individuals (Moser & Dilling, 2007). The action gains popularity non-linearly as more actors engage with it. Meanwhile, social contagion, like epidemiological contagion, is a system of agents who transmit by contact with other agents within a connected network (Christakis & Fowler, 2013). As a socially contagious concept gains popularity the number of spreaders increases, resulting in a non-linear trend (Baranzini et al., 2017). When the number of contagious agents reaches critical mass a climate social tipping point is reached, for example in Barrios-O'Neill (2021).

This research looks at the potential contribution of dietary change using contagion theory to forge a tipping point for meeting the climate challenge of 1.5°C global warming set out by the Paris Agreement 2015. Plant-based diets, or vegan diets, are generally accepted to be the least GHG-intensive of western diet trends (Chai et al., 2019). A number of studies have compared and contrasted diet regimes under different contexts, including Canada (MacRae et al., 2013; Veeramani et al., 2017), USA (Goldstein, Moses, et al., 2017), United Kingdom (Rippin et al., 2021), Europe (Cusworth et al., 2021; Detzel et al., 2021; Farchi et al., 2017), and globally (Ilea, 2009; Lynch et al., 2018; Poore & Nemecek, 2018; Rippin et al., 2021). Reducing this carbon "foodprint" is considered a crucial movement towards global climate action (Errickson et al., 2021). Replacing animal foods with novel plant proteins, such as legume products, and thus broadening the protein market is necessary for increasing widespread uptake of veganism. This is especially true of urban food systems, known as the urban "foodprint", where wealth is high and matches high animal-food consumption, but where environmentally altruistic values are concentrated (Goldstein, Birkved, et al., 2017). Food choices are often embedded in strongly held belief systems and cultural rites which makes heavy-handed governance unpalatable (Goldstein et al., 2016). However, there is room for encouraging environmentally altruistic behaviour through nudging urban social networks (Dietz et al., 2013; Kalof et al., 1999; Stern et al., 1999).

Nudging is a strategy for influencing behaviour change, such as shifting consumer demand away from environmentally damaging goods and services to less damaging alternatives (Vandenbroele et al., 2020). For example, one experiment found that marketing a plant-based meal as the dish of the day increased a catering service's plant-based demand to 85% (Perez-Cueto, 2021), thus lowering the services' indirect GHGs. Other studies have reached similar conclusions (Hansen et al., 2021). Food choices are complex and multifaceted according to personal circumstances (Perez-Cueto & Olsen, 2020). Often they do not align with nutritional or environmental guidelines (Ensaff, 2021), and food consumer governance is likely to be considered an overreach even if it may be effective in curtailing GHGs from food production systems (Goldstein et al., 2016). Research has also shown that exposure to information may be less effective at behaviour change than peer influence (Balmford et al., 2017; Morren et al., 2021).

This research explores the carbon "foodprint" of a fictitious city called Veganville subject to a range of social contagion scenarios implemented in a SES model. The metaphor of the road to Veganville was discussed by author Tobias Leenaert in his book *How to Create a Vegan World: A Pragmatic Approach (Leenaert, 2017)*. Leenaert's Veganville is positioned on a hill, and the road to it is steep, illustrating the difficult journey. His metaphor extends to the type of resting places that travellers might need to make the journey appealing. In this paper I explore the spread of veganism among a mostly omnivorous population using social contagion theory to understand the consequences for climate change. It should be noted that veganism is actually an ethical lifestyle which goes beyond a food regime including disuse of animal textiles, vivisection, and animals in entertainment. However, this study only considers the consequences of the dietary component of veganism – i.e. a plant-based diet – which is known to have strong implications on environmental and ecological impacts. Thereby the study of the journey to Veganville is used to illustrate the link between contagion theory and SES.

The objective of this research is to conceptualise and define an intersection between the established – but so far distinct – disciplines of contagion theory and SES. This paper posits that contagion theory is necessary to leverage climate social tipping points (Lenton, 2014), and thus mobilise society towards meeting global warming objectives (Otto, 2020) in lieu of underwhelming and unfit-for-purpose policy-making. I go on to discuss the efficacy of leverage points for tipping this socio-ecological system with respect to urban climate governance and nudging theory.

Materials And Methods

From Montreal to Veganville

Veganville is a conceptual city whose inhabitants' pathway to plant-based diets is used to develop the plausibility of vegan social contagion propagating a climate social tipping point. Real data are taken from Montreal, Canada, a city of approximately 2 million inhabitants (Ville de Montréal, 2017). Montreal is defined as the agglomeration of 15 municipalities on the Island of Montreal. The case study runs from 2000 to 2030 estimating the course of Montreal's historical carbon foodprint until 2018, and simulating carbon foodprint pathways from 2018 and 2030.

Population dynamics

Montreal's population is modelled in eight age cohorts. An inhabitant may die during any cohort although the mortality rate of each cohort differs. Babies are born into cohort 1 while immigrants enter cohorts 1-7, but not the elderly cohort 8. It is assumed only cohorts 4-6 reproduce. Therefore, the dietary characterisation of babies is weighted by that of cohorts 4-6 (i.e. parents choose how the new generation will eat). This indicator is called "status quo". In the case of our hypothetical city Veganville, net immigration rates for each age cohort are data from the agglomeration of Montréal (Statistics Canada, 2017), where the research took place, while cohort-specific fertility and mortality rates are taken from the Québec Institute of Statistics (Institut de la statistique du Québec, 2021a, 2021c). Initial population count for 2020 was taken from Institut de la statistique du Québec (2021b). Population variables are available in **Supplementary table 1: population.**

Dietary profiles

The dietary change assumes two diet profiles: standard omnivore diet (SOD) and plant-based diet (PBD). The SOD is defined by the average Canadian intake of each food, excluding all specifically plant-based substitutes and by adjusting animal-based foods set to the "eater" value defined in Health Canada (2018). The PBD is defined by the average Canadian intake of each food, excluding all animal-based foods with calorifically-equivalent amounts of substitute plant-based foods. This way both dietary profiles provide the same calories for each cohort. Foods are consumed in different quantities by different age groups. As the age structure of the population changes so too does the food consumption profile of the city. These data are available in **Supplementary table 2: food.**

Social contagion

The social contagion model traces the spread of veganism across a population that is either vegan or non-vegan. Contagion of veganism is influenced by the reproduction value, r, defined as the number of individuals each contagious individual infects per time step (i.e. per year). Unique r values can be applied to each age cohort and adjusted to explore scenarios for high and low reproduction, and mixed reproduction rates between the age cohorts.

A variable called fixation is the portion of individuals who become fixed in the vegan ideology until the end of the time step. It is the compliment of the recovery rate used in epidemiological contagion models. The fixation rate, f, is used to explore different thresholds of “stickiness” of ideas for the different age cohorts. For example, younger people might be more willing to adopt an idea (higher r value), but be interested in the idea for a shorter time period (less fixed).

Exchanges between omnivore to vegan is determined by the product of status quo and r value. Status quo (sq) is a variable simply defined as the ratio of omnivore population to total population. Exchange from contagious to non-contagious is determined by the product of contagious, status quo, and the difference between 1 and f. A low status quo value and a high attachment value will result in low portions of the contagious cohort reverting to be non-contagious.

New entrants to the social system, either new-borns or new immigrants, are distributed into the two cohorts weighted by the status quo. The number of new entrants joining the non-contagious cohort at any given time step is the product of the total new entrants and status quo. This is further distinguished by age cohorts. The remaining new entrants join the contagious cohort, also distinguished by age cohort. A dynamic feature of this approach is that as the status quo changes over time the heaping of new entrants changes too, creating a reinforcing feedback loop. Using this approach, we can observe how generational perspectives shift through Montreal’s population. Values and variables used for the socio-ecological contagion model are found in **Supplementary table 3: variables and equations**

Carbon foodprint

The social contagion model is used to calculate a carbon “foodprint” of the city. The foodprint is the sum of GHGs throughout the life cycle of the city’s food consumption (Goldstein, Birkved, et al., 2017).The foodprint of Montreal is calculated for each time step depending on the current age structure and adoption of veganism. Food-related GHGs are estimated as the sum of products of mass of each food type and the emission factor (EF) for each food type. The EF of each food type is made of two parts: cradle-to-use gate, and use gate-to-grave. Cradle-to-use gate accounts for the GHGs emitted during extraction of resources, farming, processing, and transport to consumer. Use gate-to-grave accounts for the GHGs emitted in waste management, which is assumed to be municipal landfill. The two life cycle phases are added to give a total EF for each food type per tonne consumed. The EFs are generated in *ecoinvent 3.4* (Wernet et al., 2016) using "ReCiPe Hierarchist" midpoint impact assessment method (Huijbregts et al., 2017) where available. EFs not available in ecoinvent were attained from literature, including pasta (Recchia et al., 2019), mushroom (Robinson et al., 2018), ice cream (Konstantas et al., 2019), baby food (Sieti et al., 2019), confectionary (Miah et al., 2018), soft drinks (Amienyo et al., 2013), game meat (Fiala et al., 2020), margarine (Nilsson et al., 2010), and sundry from Poore and Nemecek (2018). Analysis of EFs was done using *OpenLCA 1.10.3* (www.openlca.org). Waste fraction of each food type was estimated based on Gooch et al. (2019). The full list of EFs is in the **Supplementary table 4: emission factors.** These EFs were used to characterise the carbon foodprint of Montreal's social contagion using the system dynamics software *SimileV6.11* (www.simulistics.com).

Scenarios

The model is run for a set of r and f covariates to test sensitivity to these inputs. The integer r is varied between 0 and 4, and f is a real number varied between 0 and 1 in intervals of 0.25 yielding 25 scenarios. This is already a large number so, for simplicity, r and f are not varied between the eight age cohorts. These are varied to find the minimum time to reach the minimum foodprint. This inflexion point is discussed in the context of tipping points. A tipping point is defined in this context as the moment at which Montreal has sufficient conditions exist in the socio-ecological system such that the contagion leads to a minimum foodprint, i.e. Veganville. The conditions are implemented in the model at the year 2020 under all scenarios.

Results And Discussion

Tipping points of the foodprint

In 2020 Montreal's carbon foodprint was approximately 3.85 tonnes CO_2-e per capita. Montreal's social contagion of veganism shows combinations of differing r and f values have significant impact on the carbon foodprint over the decade (**Table 1**).

Table 1. Sensitivity of Montreal's estimated carbon foodprint on reproduction (r) and fixation (f) values in 2030. Values in tonnes CO_2-e per capita. Upper quartile values are shaded red, fourth quartile shaded dark red, and minimum value is shaded gold.

f r	0	1	2	3	4
0	3.90	3.90	3.90	3.90	3.90
0.25	3.90	3.78	2.28	1.97	1.97
0.5	3.90	2.81	1.97	1.97	1.97
0.75	3.90	1.97	1.97	1.97	1.97
1	3.90	1.97	1.97	1.97	1.97

Results are sensitive to variations in both r and f. As to be expected, if r=0 (no reproduction) the vegans are slowly removed from the population. On the other hand if f=0 but r>0 vegans are not removed, but they do not reproduce. Under those conditions, the carbon foodprint changes very little over the decade, and those changes are in the order of kilograms per person. All other couplings of r and f result in the carbon foodprint reaching a minimum value of approximately 1.97 tonnes CO_2-e per capita. Those minima are reached at different years and their values vary very slightly. The slight variation is due to differences in age structure of the year in which the scenario reaches the minimum. For example, an entirely vegan population higher in children will have a lower carbon foodprint than an entirely vegan population higher in older age groups. That is because the types of food consumed by each age cohort have different global warming potentials.

Conditions sufficient for a tipping point in Montreal require that social contagion leads to a minimum foodprint of 1.97 t CO_2-e per capita before 2030. Analysis of the scenarios in **Table 1** shows a minimum foodprint can be reached as early as 2023 under the most extreme r and f values, just three years after the tipping point. Tipping points occur earliest for all values of r when f is maximised at 1, and these are shown by the flattening of the foodprint curves in **Figure 1**.

Tipping points are also identified for f<1. In these cases, if r=1, the minimum can be reached in 2030 with the tipping point in the range 0.5<f≤0.75, meaning that if every vegan influences 1 omnivore to try being vegan every year, between half and three-quarters of those influenced must remain vegan for the duration of the year to reach the minimum. For r=2, the minimum is reached in 2029 with the tipping point in the range 0.25<f≤0.5, meaning that if every vegan influences 2 omnivores to try being vegan every year, no more than half of those influenced must remain vegan for the duration of the year to reach the minimum. For r=3, the minimum is reached in 2030 with the tipping point in the range 0<f≤0.25, meaning if every vegan influences 3 omnivores to try being vegan every year, no more than a quarter must remain vegan for the duration of the year to reach the minimum. Finally, for r=4 the minimum is reached in 2029 with the tipping point also in the range 0<f≤0.25.

In the best-case scenario, Montreal's carbon foodprint falls to a minimum of 1.97 t CO_2-e per person in 2023 with f=1 when r= 3 or 4. This shows tipping is less sensitive to increasing reproduction when fixation is high.

Regardless of the year it is achieved, this minimum amounts to chopping the 2020 foodprint by almost 50% over ten years. When we consider the aim to reach as little as 2.9 t CO_2-e per person by 2030, Montreal's minimum only allows less than one tonne per person for all other sources of emission. This aligns with the findings of Crippa et al. (2021) that one third of anthropogenic GHGs are from the food system.

In other words, the other ≈ 35 Gt CO_2-e released annually outside the global food system – amounting to around 4.8 t CO_2-e per capita – must squeeze down to a fifth that amount. This shows that widespread changes to the food system's GHGs are necessary but insufficient if we are to meet the 1.5°C target. This is underscored by the most recent reports from the Intergovernmental Panel on Climate Change (IPCC, 2022a, 2022b) who clearly outline a need to transition to plant-based foods.

Running with this lower limit of 1.97 t CO_2-e per capita as the best possible outcome, the r=3, f=1 scenario is developed further to illustrate the influence social contagion has on Montreal's carbon foodprint over different age cohorts over time. The foodprint varies by age cohort due to the influence of age on food preferences, and the lag of the model taking longer to reproduce vegan contagion in older people.

Governance and nudging

Shifting away from animal-based diets towards plant-based diets is a very useful piece in the climate mitigation puzzle. Behaviour change has great potential to positively influence the climate emergency, but getting that behaviour to change is difficult. Priorities and belief systems vary making individual behaviour a wicked problem to solve (Perez-Cueto & Olsen, 2020), and exposure to robust information is known to not always work (Morren et al., 2021). Given the reluctance to legislate for climate-friendlier food choices, government-led communication nudging to increase the reproduction value and fixation rate may be a useful solution toward a climate social tipping point (Moser & Dilling, 2007). Nudging up the reproduction value and the fixation rate a small amount will have a profound impact on the decarbonisation of food. In the vegan social contagion case, consumers could be nudged towards purchasing items that substitute animal-based products (Morren et al., 2021), such as communicating through environmental product declarations on food packaging (Vandenbroele et al., 2020) and re-articulating official public dietary advice (Ensaff, 2021). This would have an impact on education leading to shifts in norms and values (Hansen et al., 2021) which would in turn reinforce policies and governance (Otto, 2020).

It has been shown that nudging interventions can be effective in this regard (Kwasny et al., 2022). For example, Hartwell et al. (2020) explored variation of vegetable consumption between age groups and regions to better understand the determinants for nudging towards higher vegetable intake, such as plant-based "dish of the day" in workplace canteens. Perez-Cueto (2021) went on to discuss the ways in which plant-based meals can be designed to increase selection by omnivores. Such approaches could be scaled up to induce demand for plant-based foods at the sector level (Garnett et al., 2019), or implemented as part of an urban sustainability plan (Elliot et al., 2020; Elliot et al., 2022). This approach could be adopted in a scaled-up part of sustainable urban planning to decrease the urban carbon foodprint of the city's residents (Elliot et al., 2018). A similar approach was adopted in Portugal, in which educational institutions are required to provide and advertise a plant-based meal option with hopes to induce demand (Cardoso et al., 2018), which is more palatable and probably more effective from a holistic SES intervention point of view (Meadows, 2008).

Socio-ecological contagion

Due to the social and ecological dynamics discussed in this paper the term **socio-ecological contagion** is proposed for use in the pursuit of socio-ecological system analysis using social contagion theory as a basis for leveraging socially-led tipping points for ecological stability. Socio-ecological contagion is defined as *the interactions between social contagion and damage done to ecological systems to measure peer-to-peer spread of environmental stewardship agendas.*

Research has emerged over the last four decades emphasising the importance of integrated social and ecological systems models. The work of Donella Meadows (Meadows & Randers, 2012; Meadows, 2008), Garrett Hardin's *The Tragedy of the Commons* (Hardin, 1968), among many others (e.g. Daily & Ehrlich, 1994; Ehrlich et al., 1992), remind us that society is part of nature and that as we exploit nature's services we in turn fill the world with substances that reduce our quality of life (Arrow et al., 2004; Costanza et al., 1997). Socio-ecological systems emerged, as did coupled human and nature systems (CHANS), to acknowledge and underscore the importance of dependencies and causal interactions between human activities and the natural world that hosts us (Costanza, 2014; Liu et al., 2007). As we approach several global ecological challenges, including climate change, biodiversity loss, and food and water security, we understand more the consequences of interconnectedness between social and ecological systems (Liu et al., 2007). Coming to terms with these overwhelming challenges we realise the importance of unified efforts to lock in ecological protections and to wind back the activities that jeopardise them (Dietz & Ostrom).

This research has looked at how an uprising of ecologically conscientious actors can spread an idea to reduce the pressure on ecosystems – in this case by reducing a city's food-related GHGs through social contagion. Results show potential for conscious consumer movement to help deal with food consumption-based environmental impacts. However, with little power to organise at the necessary level to affect meaningful change, the individual should not be burdened with this task alone. Instead, I argue that governing bodies, especially at the municipal level, look for ways to implement nudging in urban food systems, and this has potential applications to other consumption-based environmental impacts such as transport mode choices. For example, encouraging plant-based dish of the day options, as shown by Hartwell et al. (2020), and teaching the environmental damage done by animal farming in schools to increase the reproduction rate among omnivores, removing financial incentives, and removing advertisements of carbon-intensive foods such as meat and dairy from education institutions to increase fixation among new vegans (Pais et al., 2021). This is expected to help cities like Montreal along the journey to Veganville (Leenaert, 2017).

Conclusions

Shifting away from animal-based diets towards plant-based diets is a very useful piece in the climate mitigation puzzle. Citizens' agency has high potential to positively influence the climate emergency. A system dynamics model is developed to implement social contagion theory in a changing urban food system and its related greenhouse gas emissions. Reproduction and fixation rates are used to study the sensitivity and timeliness of the urban carbon foodprint, and the numerical results are discussed in the context of the 1.5°C Paris Agreement target. The foodprint can be reduced significantly with widespread adoption of veganism, particularly by the concept of nudging, but the foodprint reaches a minimum at 1.97 tonnes CO_2-equivalent per capita. Under maximal contagion scenario the minimum foodprint is reached just three years after tipping point intervention. Social contagion is identified as a catalyst for social tipping points, and emission pathways are explored with a variety of different contagion variables to test sensitivity towards a tipping point. Tipping the foodprint pathway to reach this minimum value requires at least a quarter of individuals should remain vegan for at least one year and influence at least three non-vegans during that period. This is significant as it demonstrates the need to embed food demand in urban climate governance such as nudging towards plant-based food alternatives. Nudging is discussed as a lever of ecological importance to social contagion which can be used to increase the reproduction value and the fixation rate to reach a tipping point earlier. Finally, the term socio-ecological contagion is introduced and defined as the interactions between social contagion and damage done to ecological systems to measure peer-to-peer spread of environmental stewardship agendas.

References

Amienyo, D., Gujba, H., Stichnothe, H., & Azapagic, A. (2013, 2013/01/01). Life cycle environmental impacts of carbonated soft drinks. *The International Journal of Life Cycle Assessment, 18*(1), 77-92. https://doi.org/10.1007/s11367-012-0459-y

Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., Levin, S., Mäler, K.-G., Schneider, S., Starrett, D., & Walker, B. (2004). Are We Consuming Too Much? *Journal of Economic Perspectives, 18*(3), 147-172. https://doi.org/10.1257/0895330042162377

Balmford, A., Cole, L., Sandbrook, C., & Fisher, B. (2017). The environmental footprints of conservationists, economists and medics compared. *Biological Conservation, 214*, 260-269. https://doi.org/10.1016/j.biocon.2017.07.035

Baranzini, A., Carattini, S., & Péclat, M. (2017). *What drives social contagion in the adoption of solar photovoltaic technology*.

Barrios-O'Neill, D. (2021). Focus and social contagion of environmental organization advocacy on Twitter. *Conservation Biology, 35*(1), 307-315.

Cardoso, S. G., Augusto, F. R., Carvalho, N., & Graça, N. J. (2018). Public support for vegetarian meals in public canteens: a preliminary study. In A. Delicado, N. Domingos, & L. d. Sousa (Eds.), *Changing Societies: Legacies and Challenges* (Vol. III The diverse worlds of sustainability). Instituto de Ciências Sociais.

Chai, B. C., van der Voort, J. R., Grofelnik, K., Eliasdottir, H. G., Klöss, I., & Perez-Cueto, F. J. A. (2019). Which Diet Has the Least Environmental Impact on Our Planet? A Systematic Review of Vegan, Vegetarian and Omnivorous Diets. *Sustainability, 11*(15). https://doi.org/10.3390/su11154110

Christakis, N. A., & Fowler, J. H. (2013, Feb 20). Social contagion theory: examining dynamic social networks and human behavior [Review]. *Stat Med, 32*(4), 556-577. https://doi.org/10.1002/sim.5408

Costanza, R. (2014). A theory of socio-ecological system change. *Journal of Bioeconomics, 16*(1), 39-44.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., & van den Belt, M. (1997, 1997/05/01). The value of the world's ecosystem services and natural capital. *Nature, 387*(6630), 253-260. https://doi.org/10.1038/387253a0

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021, 2021/03/01). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food, 2*(3), 198-209. https://doi.org/10.1038/s43016-021-00225-9

Cusworth, G., Garnett, T., & Lorimer, J. (2021, 2021/07/01/). Legume dreams: The contested futures of sustainable plant-based food systems in Europe. *Global environmental change, 69*, 102321. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2021.102321

Daily, G. C., & Ehrlich, P. R. (1994). Population, sustainability, and Earth's carrying capacity. In *Ecosystem Management* (pp. 435-450). Springer.

Detzel, A., Krüger, M., Busch, M., Blanco, I., Varela, C., Manners, R., Bez, J., & Zannini, E. (2021, 2021/07/07). Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: An environmental perspective. *Journal of the Science of Food and Agriculture*. https://doi.org/https://doi.org/10.1002/jsfa.11417

Dietz, T., & Ostrom, E. P. Stern 2003. The struggle to govern the commons. *Science, 302*(5652), 1907-1912.

Dietz, T., Stern, P. C., & Weber, E. U. (2013). Reducing Carbon-Based Energy Consumption through Changes in Household Behavior. *Daedalus, 142*(1), 78-89. https://doi.org/10.1162/DAED_a_00186

Ehrlich, P. R., Ehrlich, A. H., & Daily, G. C. (1992). *Population, ecosystem services, and the human food supply*.

Elliot, T., Babí Almenar, J., & Rugani, B. (2020). Impacts of policy on urban energy metabolism at tackling climate change: The case of Lisbon. *Journal of Cleaner Production, 276*. https://doi.org/10.1016/j.jclepro.2020.123510

Elliot, T., Rugani, B., Almenar, J. B., & Niza, S. (2018). A Proposal to Integrate System Dynamics and Carbon Metabolism for Urban Planning. *Procedia CIRP, 69*, 78-82. https://doi.org/10.1016/j.procir.2017.10.003

Elliot, T., Torres-Matallana, J. A., Goldstein, B., Babí Almenar, J., Gómez-Baggethun, E., Proença, V., & Rugani, B. (2022, 2022/07/01/). An expanded framing of ecosystem services is needed for a sustainable urban future. *Renewable and Sustainable Energy Reviews, 162*, 112418. https://doi.org/https://doi.org/10.1016/j.rser.2022.112418

Ensaff, H. (2021, May). A nudge in the right direction: the role of food choice architecture in changing populations' diets. *Proc Nutr Soc, 80*(2), 195-206. https://doi.org/10.1017/S0029665120007983

Errickson, F., Kuruc, K., & McFadden, J. (2021, 2021/04/01). Animal-based foods have high social and climate costs. *Nature Food, 2*(4), 274-281. https://doi.org/10.1038/s43016-021-00265-1

Farchi, S., De Sario, M., Lapucci, E., Davoli, M., & Michelozzi, P. (2017). Meat consumption reduction in Italian regions: Health co-benefits and decreases in GHG emissions. *PLOS ONE, 12*(8), e0182960. https://doi.org/10.1371/journal.pone.0182960

Fiala, M., Marveggio, D., Viganò, R., Demartini, E., Nonini, L., & Gaviglio, A. (2020). LCA and wild animals: Results from wild deer culled in a northern Italy hunting district. *Journal of Cleaner Production, 244*. https://doi.org/10.1016/j.jclepro.2019.118667

Garnett, E. E., Balmford, A., Sandbrook, C., Pilling, M. A., & Marteau, T. M. (2019, Oct 15). Impact of increasing vegetarian availability on meal selection and sales in cafeterias [Observational Study

Research Support, Non-U.S. Gov't]. *Proc Natl Acad Sci U S A, 116*(42), 20923-20929. https://doi.org/10.1073/pnas.1907207116

Goldstein, B., Birkved, M., Fernández, J., & Hauschild, M. (2017, 2017/02/01). Surveying the Environmental Footprint of Urban Food Consumption. *Journal of Industrial Ecology, 21*(1), 151-165. https://doi.org/https://doi.org/10.1111/jiec.12384

Goldstein, B., Hansen, S. F., Gjerris, M., Laurent, A., & Birkved, M. (2016, 2016/02/01/). Ethical aspects of life cycle assessments of diets. *Food Policy, 59*, 139-151.

https://doi.org/https://doi.org/10.1016/j.foodpol.2016.01.006

Goldstein, B., Moses, R., Sammons, N., & Birkved, M. (2017). Potential to curb the environmental burdens of American beef consumption using a novel plant-based beef substitute. *PLOS ONE, 12*(12), e0189029. https://doi.org/10.1371/journal.pone.0189029

Gooch, M., Bucknell, D., LaPlain, D., Dent, B., Whitehead, P., Felfel, A., Nikkel, L., & Maguire, M. (2019). The Avoidable Crisis of Food Waste: Technical Report; Value Chain Management International and Second Harvest. *Ontario, Canada*. www.SecondHarvest.ca/Research

Hansen, P. G., Schilling, M., & Malthesen, M. S. (2021, Jun 7). Nudging healthy and sustainable food choices: three randomized controlled field experiments using a vegetarian lunch-default as a normative signal. *J Public Health (Oxf), 43*(2), 392-397. https://doi.org/10.1093/pubmed/fdz154

Hardin, G. (1968, 1968/12/13). The Tragedy of the Commons. *Science, 162*(3859), 1243-1248. https://doi.org/10.1126/science.162.3859.1243

Hartwell, H., Bray, J., Lavrushkina, N., Rodrigues, V., Saulais, L., Giboreau, A., Perez-Cueto, F. J. A., Monteleone, E., Depezay, L., & Appleton, K. M. (2020, 2020/12/01). Increasing vegetable consumption out-of-home: VeggiEAT and Veg+projects [https://doi.org/10.1111/nbu.12464]. *Nutrition Bulletin, 45*(4), 424-431. https://doi.org/https://doi.org/10.1111/nbu.12464

[Record #61 is using a reference type undefined in this output style.]

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017, 2017/02/01). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment, 22*(2), 138-147. https://doi.org/10.1007/s11367-016-1246-y

Ilea, R. C. (2009, 2009/04/01). Intensive Livestock Farming: Global Trends, Increased Environmental Concerns, and Ethical Solutions. *Journal of Agricultural and Environmental Ethics, 22*(2), 153-167. https://doi.org/10.1007/s10806-008-9136-3

Institut de la statistique du Québec. (2021a). *Death rate by age group and sex, Québec, 2016-2020*. https://statistique.quebec.ca/en/document/deaths-quebec/tableau/death-rate-by-age-group-and-sex-quebec

Institut de la statistique du Québec. (2021b). *Estimations de la population des régions administratives, Québec, 1er juillet 1986 à 2020*. https://statistique.quebec.ca/en/document/population-and-age-and-sex-structure-administrative-regions/tableau/estimations-population-regions-administratives

Institut de la statistique du Québec. (2021c). *Naissances et taux de natalité, Québec, 1900-2020*. https://statistique.quebec.ca/fr/produit/tableau/naissances-et-taux-de-natalite-quebec

IPCC. (2022a). *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. C. U. Press.

IPCC. (2022b). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. C. U. Press.

Kalof, L., Dietz, T., Stern, P. C., & Guagnano, G. A. (1999, 1999/09/01). Social Psychological and Structural Influences on Vegetarian Beliefs. *Rural Sociology, 64*(3), 500-511. https://doi.org/https://doi.org/10.1111/j.1549-0831.1999.tb00364.x

Konstantas, A., Stamford, L., & Azapagic, A. (2019). Environmental impacts of ice cream. *Journal of Cleaner Production, 209*, 259-272. https://doi.org/10.1016/j.jclepro.2018.10.237

Kwasny, T., Dobernig, K., & Riefler, P. (2022, Jan 1). Towards reduced meat consumption: A systematic literature review of intervention effectiveness, 2001-2019 [Research Support, Non-U.S. Gov't

Systematic Review]. *Appetite, 168*, 105739. https://doi.org/10.1016/j.appet.2021.105739

Leenaert, T. (2017). *How to Create a Vegan World: A Pragmatic Approach*. Lantern Publishing & Media.

Lenton, T. M. (2014). Tipping climate cooperation. *Nature Climate Change, 4*(1), 14-15.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H., & Taylor, W. W. (2007). Complexity of Coupled Human and Natural Systems. *Science, 317*(5844), 1513. https://doi.org/10.1126/science.1144004

Lynch, H., Johnston, C., & Wharton, C. (2018, Dec 1). Plant-Based Diets: Considerations for Environmental Impact, Protein Quality, and Exercise Performance [Review]. *Nutrients, 10*(12). https://doi.org/10.3390/nu10121841

MacRae, R., Cuddeford, V., Young, S. B., & Matsubuchi-Shaw, M. (2013). The Food System and Climate Change: An Exploration of Emerging Strategies to Reduce GHG Emissions in Canada. *Agroecology and Sustainable Food Systems, 37*(8), 933-963. https://doi.org/10.1080/21683565.2013.774302

Meadows, D., & Randers, J. (2012). *The limits to growth: the 30-year update*. Routledge.

Meadows, D. H. (2008). *Thinking in systems: A primer*. chelsea green publishing.

Miah, J. H., Griffiths, A., McNeill, R., Halvorson, S., Schenker, U., Espinoza-Orias, N. D., Morse, S., Yang, A., & Sadhukhan, J. (2018). Environmental management of confectionery products: Life cycle impacts and improvement strategies. *Journal of Cleaner Production, 177*, 732-751. https://doi.org/10.1016/j.jclepro.2017.12.073

Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J. F., Mathias, J.-D., Rocha, J. C., Schoon, M., & Werners, S. E. (2018). Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. *Environmental Research Letters, 13*(3). https://doi.org/10.1088/1748-9326/aaaa75

Morren, M., Mol, J. M., Blasch, J. E., & Malek, Ž. (2021). Changing diets - Testing the impact of knowledge and information nudges on sustainable dietary choices. *Journal of Environmental Psychology, 75*. https://doi.org/10.1016/j.jenvp.2021.101610

Moser, S. C., & Dilling, L. (2007). Toward the social tipping point: Creating a climate for change. *Creating a climate for change: Communicating climate change and facilitating social change*, 491-516.

Nilsson, K., Flysjö, A., Davis, J., Sim, S., Unger, N., & Bell, S. (2010). Comparative life cycle assessment of margarine and butter consumed in the UK, Germany and France. *The International Journal of Life Cycle Assessment, 15*(9), 916-926. https://doi.org/10.1007/s11367-010-0220-3

Otto, I. M. D., Jonathan F.; Cremades, Roger; Bhowmik, Avit; Hewitt, Richard J.; Lucht, Wolfgang; Rockström, Johan; Allerberger, Franziska; McCaffrey, Mark; Doe, Sylvanus S. P. (2020). Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences, 117*(5), 2354-2365.

Pais, D. F., Marques, A. C., & Fuinhas, J. A. (2021). Drivers of a new dietary transition towards a sustainable and healthy future. *Cleaner and Responsible Consumption, 3*. https://doi.org/10.1016/j.clrc.2021.100025

Perez-Cueto, F. J. A. (2021). Nudging plant-based meals through the menu. *International Journal of Gastronomy and Food Science, 24*. https://doi.org/10.1016/j.ijgfs.2021.100346

Perez-Cueto, F. J. A., & Olsen, A. (2020, Feb 16). The Multifaceted Dimensions of Food Choice and Nutrition [Editorial

Introductory]. *Nutrients, 12*(2). https://doi.org/10.3390/nu12020502

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science, 360*(6392), 987-992. https://doi.org/10.1126/science.aaq0216

Recchia, L., Cappelli, A., Cini, E., Garbati Pegna, F., & Boncinelli, P. (2019). Environmental Sustainability of Pasta Production Chains: An Integrated Approach for Comparing Local and Global Chains. *Resources, 8*(1). https://doi.org/10.3390/resources8010056

Rippin, H. L., Cade, J. E., Berrang-Ford, L., Benton, T. G., Hancock, N., & Greenwood, D. C. (2021). Variations in greenhouse gas emissions of individual diets: Associations between the greenhouse gas emissions and nutrient intake in the United Kingdom [Research Support, Non-U.S. Gov't]. *PLOS ONE, 16*(11), e0259418. https://doi.org/10.1371/journal.pone.0259418

Robinson, B., Winans, K., Kendall, A., Dlott, J., & Dlott, F. (2018). A life cycle assessment of Agaricus bisporus mushroom production in the USA. *The International Journal of Life Cycle Assessment, 24*(3), 456-467. https://doi.org/10.1007/s11367-018-1456-6

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlík, P., Humpenöder, F., Stehfest, E., & Tavoni, M. (2018, 2018/04/01). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change, 8*(4), 325-332. https://doi.org/10.1038/s41558-018-0091-3

Sieti, N., Schmidt Rivera, X. C., Stamford, L., & Azapagic, A. (2019, Nov 1). Environmental sustainability assessment of ready-made baby foods: Meals, menus and diets. *Sci Total Environ, 689*, 899-911. https://doi.org/10.1016/j.scitotenv.2019.06.363

[Record #74 is using a reference type undefined in this output style.]

Stern, P. C., Dietz, T., Abel, T., Guagnano, G. A., & Kalof, L. (1999). A Value-Belief-Norm Theory of Support for Social Movements: The Case of Environmentalism. *Human Ecology Review, 6*(2), 81-97. http://www.jstor.org/stable/24707060

United Nations. (2019). *World Population Prospects 2019: Highlights* (ST/ESA/SER.A/423).

Vandenbroele, J., Vermeir, I., Geuens, M., Slabbinck, H., & Van Kerckhove, A. (2020, Feb). Nudging to get our food choices on a sustainable track [Research Support, Non-U.S. Gov't Review]. *Proc Nutr Soc, 79*(1), 133-146. https://doi.org/10.1017/S0029665119000971

Veeramani, A., Dias, G. M., & Kirkpatrick, S. I. (2017). Carbon footprint of dietary patterns in Ontario, Canada: A case study based on actual food consumption. *Journal of Cleaner Production, 162*, 1398-1406. https://doi.org/10.1016/j.jclepro.2017.06.025

Ville de Montréal. (2017). *Population et démgraphie*.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016, 2016/09/01). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*(9), 1218-1230. https://doi.org/10.1007/s11367-016-1087-8

WRI. (2021). *Climate Watch historical GHG emissions* https://www.climatewatchdata.org/ghg-emissions?end_year=2018&start_year=1990

Figures

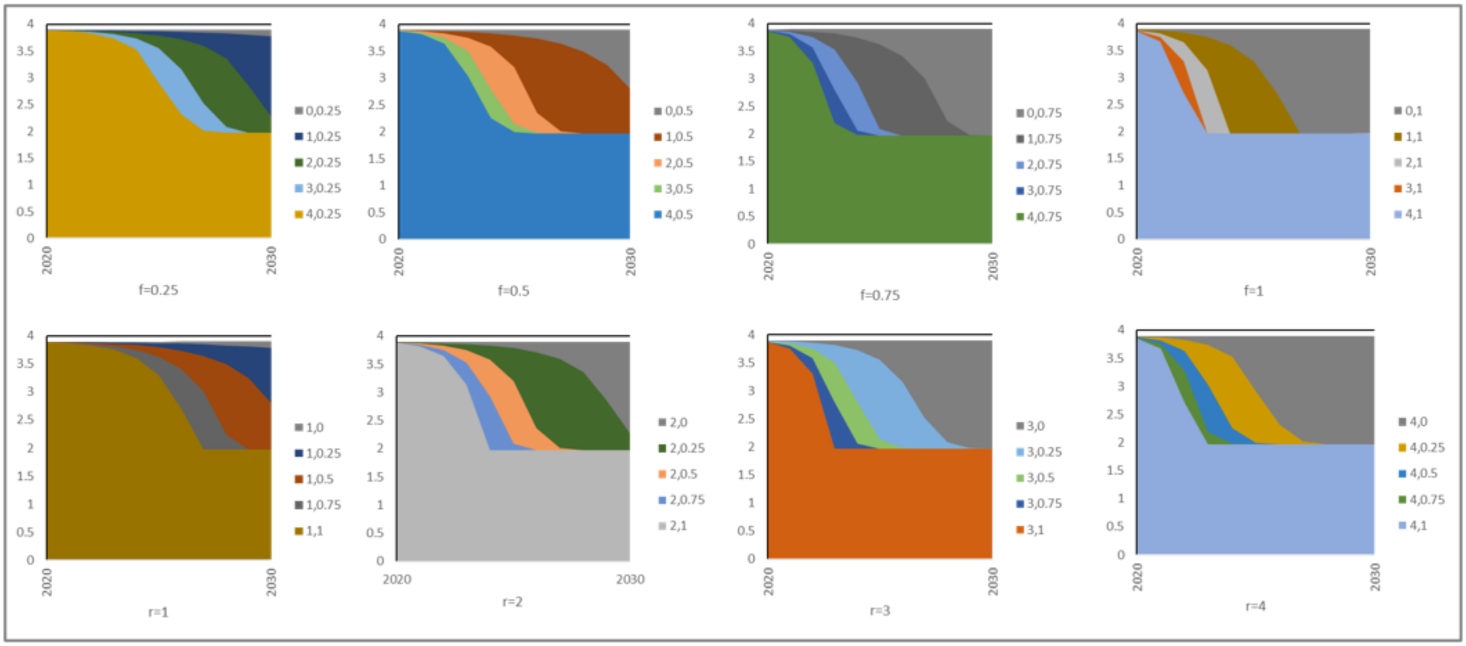

Figure 1

Carbon foodprint per capita from 2020 to 2030 for all scenarios. Top row shows scenarios with f value held constant by varying r for each f interval. Bottom row shows scenarios with r value held constant by varying f for each r interval.

Supplementary Files

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