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Conceptualising the drivers of ultra-processed food production and consumption and their environmental impacts: a group model-building exercise

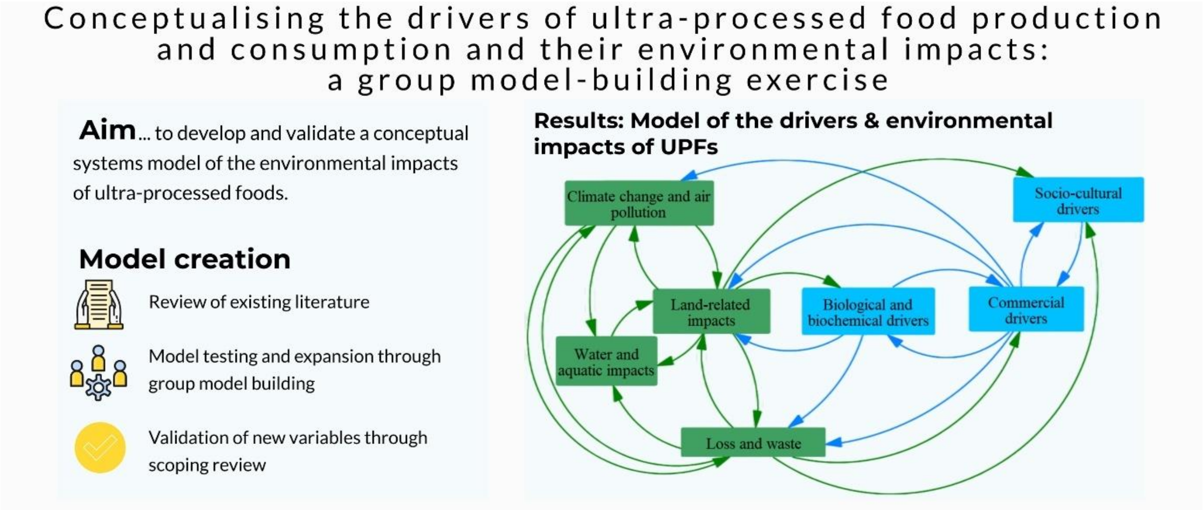
Abstract

Using group model building we developed a series of causal loop diagrams identifying the environmental impacts of ultra-processed food (UPF) systems, and underlying system drivers, which was subsequently validated against the peer-reviewed literature. The final conceptual model displays the commercial, biological and social drivers of the UPF system, and the impacts on environmental sub-systems including climate, land, water and waste. It displays complex interactions between various environmental impacts, demonstrating how changes to one component of the system could have flow-on effects on other components. Trade-offs and uncertainties are discussed. The model has a wide range of applications including informing the design of quantitative analyses, identifying research gaps and potential policy trade-offs resulting from a reduction of ultra-processed food production and consumption.

Keywords

- Ultra-processed foods
- Sustainable diets
- Group model building
- Food system transformation
- Environmental impact assessment

Graphical abstract



Conceptualising the drivers of ultra-processed food production and consumption and their environmental impacts: a group model-building exercise

Aim... to develop and validate a conceptual systems model of the environmental impacts of ultra-processed foods.

Model creation

- Review of existing literature
- Model testing and expansion through group model building
- Validation of new variables through scoping review

Results: Model of the drivers & environmental impacts of UPFs

1. Introduction

The global food system is a leading driver of environmental degradation (Tilman and Clark, 2014; Willett et al., 2019). It is responsible for one-third of global greenhouse gas emissions (Crippa et al., 2021), approximately 70% of freshwater use (Earthscan, 2007), is the largest driver of land and marine ecosystem biodiversity loss (Benton et al., 2021), and threatens freshwater and marine ecosystems through the excessive use of nitrogen and phosphorus-based production inputs (Diaz and Rosenberg, 2008). Transitioning to a healthy and sustainable food system is essential to meet global environmental targets, including the Paris Climate Agreement and the Sustainable Development Goals (Chen et al., 2022; Rockström et al., 2020).

One approach to improve the sustainability of diets is to reduce the production and consumption of ultra-processed foods (UPFs) (Fardet and Rock, 2020; Seferidi et al., 2020). UPFs form the fourth group of the NOVA (a name, not an acronym) food classification system, which defines UPFs as '*formulations of ingredients, mostly of exclusive industrial use, that result from a series of industrial processes'* (Monteiro et al., 2019). Examples of UPFs include sugar-sweetened beverages, confectionary, packaged snacks, ready-made infant foods, breakfast cereals and reconstituted meats (Monteiro et al., 2019). The other three groups are unprocessed/ minimally processed foods (Group 1), processed culinary ingredients (Group 2) and processed foods (Group 3) (Monteiro et al., 2019). NOVA groups 1-3 are collectively referred to as non-UPFs throughout the text. UPFs are associated with multiple adverse health outcomes, such as cancer, type-2 diabetes and cardiovascular diseases (Chen et al., 2020; Elizabeth et al., 2020; Lane et al., 2021; Pagliai et al., 2021). UPFs are predominantly discretionary in nature, and easily overconsumed (Forde et al., 2020). UPFs comprise a large proportion (10-60%) of total dietary energy intake in high-income countries (Marino et al., 2021), with consumption rapidly rising in middle-income countries (Baker et al., 2020; Monteiro et al., 2013). While reformulating these products to improve their nutrient composition may reduce some adverse health impacts associated with their consumption, it does not necessarily transform them into ‘healthful’ foods (Scrinis and Monteiro, 2018), and will not materially reduce their environmental impacts. Therefore, a reduction in UPF production and consumption could reduce environmental impacts from foods which are often superfluous to human needs (Hadjikakou, 2017).

Quantitative evidence on the environmental impact of UPFs is limited to two published studies from Brazil (da Silva et al., 2021; Garzillo et al., 2022) and one from France (Kesse-Guyot et al., 2022). These studies indicate that UPFs can significantly contribute to diet-related greenhouse gas emissions, land-use, energy and water-footprints (Kesse-Guyot et al., 2022), driven primarily by overconsumption (da Silva et al., 2021; Garzillo et al., 2022). Reviews of the literature suggest that the production of UPFs may be associated with large-scale monoculture farming, high energy-inputs for processing, lengthy transportation chains and excessive packaging (Anastasiou et al., 2022; Fardet and Rock, 2020; Seferidi et al., 2020). As a result, relationships between UPF production and biodiversity loss, greenhouse gas emissions, waste, land degradation and impacts on water quality and scarcity have been proposed (Anastasiou et al., 2022; Fardet and Rock, 2020; Leite et al., 2022).

Understanding the environmental impacts of UPFs comes with challenges. First, all supply chain stages must be included (Seferidi et al., 2020), and differentiated. Existing research has not differentiated between the environmental impacts of primary processing (essential processes that increase shelf-life or digestibility while preserving the original ingredients, such as milling or fermentation) and ultra-processing, which is unessential. This is important because identifying environmental impacts at key supply chain stages may enable more informed and effective interventions.

Second, impacts are often measured in isolation, with limited consideration of the environmental processes that link impacts across the system (Aldaya et al., 2021). Even empirical analyses that consider more than one metric (e.g. greenhouse gas emissions, water-scarcity and biodiversity loss) rarely consider how such environmental impacts may interact. This is important because ecosystems and food systems are highly dynamic; changes in one part of the system can have significant flow-on impacts and trade-offs with other system components (Campbell et al., 2018). The need for a more cross-disciplinary food systems approach was emphasised in the 2021 UN Food Systems Summit and recent reports (Rockström et al., 2020), which highlight the urgent need to achieve a food systems transition and minimise systems trade-offs to meet global targets including the Paris Climate Agreement (Zurek et al., 2022) and the Sustainable Development Goals (von Braun et al., 2021).

This study aims to develop and validate a conceptual model of the known and potential environmental impacts across ultra-processed food systems. This study a) identifies key variables that drive UPF systems; b) conceptualises the relationships between environmental impacts and each stage of UPF systems and; c) differentiates the environmental, economic, social and biological impacts of ultra-processed food systems relative to those producing non-UPFs.

2. Methods

Systems dynamics is a field of science used to understand complex behaviours of systems (Haji Gholam Saryazdi et al., 2021), and can be used to address the limitations described in the introduction. Group model building (GMB) is a soft systems method whereby a qualitative systems model is developed and then tested via modelling workshops with experts and key stakeholders (Vennix, 1996). Previous studies have identified that GMB enables diverse discussions of complex social, economic and environmental phenomena (Valencia Cotera et al., 2022), while generating new knowledge and sensitising stakeholders to a given issue (Rouwette et al., 2002).

Causal loop diagrams (CLDs) are ideal for displaying dynamic relationships between key variables in complex systems (Purwanto et al., 2019). CLDs comprise of variables that can increase or decrease; arrows containing a polarity indicator (+/-) that indicate the direction of the association, e.g. where a positive polarity indicates that the variables are moving in the same direction; reinforcing loops (shown as ‘R’ with a circular arrow), that indicate a positive feedback loop whereby both variables A and B increase; and balancing loops (shown as ‘B’ with a circular arrow), that indicate a feedback loop whereby one variable increases and the other decreases. This study used group model building (GMB) to test and validate a CLD.

2.1 Developing the initial causal loop diagram

Following standard GMB practice (Haji Gholam Saryazdi et al., 2021), a preliminary CLD was developed as follows. Initial variables were sourced from scientific papers and reports identified in a recently published review (Anastasiou et al., 2022) on the characteristics of UPFs and relationships with the natural environment. Key UPF supply chain stages were adapted from the published review (see Appendix). After these resources were exhausted, searches of the peer-reviewed literature were conducted in EbscoHost to ascertain if there were known relationships between each of the initially identified variables. Studies were included if they described the relationships between two variables (see Appendix). Reviews and reports which provided consensus statements from authoritative organisations, such as the Food and Agriculture Organisation of the United Nations and the Intergovernmental Panel on Climate Change, were prioritised. Where necessary, additional variables were added to explain the pathways between variables previously identified.

2.2 Group model building process

For the GMB workshops, 19 experts on sustainable food systems were identified through published literature, according to purposive sampling methods (Tongco, 2007). Of these, 11 participants from Australasia, Asia, Europe, North America and South America consented and attended one of three two-hour online workshops facilitated by the lead author. Three participants were from low or middle-income countries. Reasons for not participating were unavailability (n=2) or no response to the email (n= 6).

The workshops followed pre-established and tested GMB scripts (see Appendix). Each workshop began with a presentation on the research aims, existing research, GMB process and model. The preliminary CLD was edited in real-time using Vensim software (Ventana Inc.), based on group discussion. Participants suggested variables, relationships and modifications to the CLD, and discussed the impacts of UPF systems compared with an idealised healthy and sustainable food system.

While participants usually agreed with each other regarding modelling decisions, occasionally disagreements occurred. In these instances, discussion was encouraged to better understand the rationale behind such differences in opinion which revealed differences in regional contexts or assumptions. This led to additional variables, clarification of assumptions, or additional trade-offs (see section 3.9).

After the workshops, the preliminary CLD was refined to reflect participant inputs and to ensure consistent granularity of variables. Rigorous criteria, such as degree of removal from the supply chain, and specificity to only one region, were applied to determine the exclusion of the variables and relationships (see Appendix). Reinforcing and balancing loops overlooked during the workshops were added at this stage.

2.3 Validation of new variables and pathways, and evaluating the strength of the evidence

Following the workshops, the model was consolidated, in accordance with standard practice (Haji Gholam Saryazdi et al., 2021). We then cross-checked the new variables and pathways by conducting an additional search for published literature and reports, and including literature suggested by participants. Lines in the model were formatted to reflect the strength of the evidence by distinguishing them according to three groups: (i) proposed, (ii) emerging, or (iii) established (definitions in the Appendix).

After the variables were finalised, the model was divided thematically into seven subsystems: three subsystems represent the drivers of UPF production (blue variables, subsystems 1-3) and another four subsystems represent the environmental impacts of the system (green variables, subsystems 4-7). Some variables and relationships appear in multiple subsystems, as subsystems do not exist in isolation.

Participants were offered the opportunity to provide feedback on the final CLDs via the draft manuscript, as a final consensus (Rouwette et al., 2002) and internal validity check. Ten participants provided feedback and elected to become co-authors which acknowledged their contribution to the model and manuscript. One participant opted out of the feedback and manuscript writing process due to time constraints.

3. Results

The seven CLDs developed in this study illustrate the widescale drivers of UPF systems and associated environmental impacts. Three CLDs display the drivers of UPF systems (Figures 1-3); four CLDs display the environmental impacts (Figures 4-7). A full model displaying all impacts is available in the Appendix. CLD variables include drivers and outcomes of the system, with changes to one part of the system resulting in flow-on impacts throughout the system. The results present key variables and interactions described by the CLD. Variables are differentiated in the manuscript text using italics. Details on each relationship, supporting evidence, and grading methods are available (see Appendix).

3.1 Summary model

The summary model displays the relationships between each subsystem, illustrating that the subsystems do not exist in isolation. Instead, there are dynamic interactions among the variables and pathways of the different CLDs; i.e. the full system is more than the sum of the individual variables or subsystems.

The summary model also highlights key system drivers. For example, commercial drivers are core to many of the other subsystems, largely because profit gains appear to drive commercial, biological and socio-cultural systems (see R1, 2 & B1-4, Figure 1).

The summary model also demonstrates that the environmental subsystems are deeply connected; each environmental subsystem is linked (Figure 1). This likely reflects the interconnected nature of ecosystems. Also of note are the many reinforcing loops between land-related impacts and other subsystems (R3-9). Thus, the land-related impacts, often initially stemming from agricultural production of UPFs, are likely key drivers of UPF environmental degradation, reinforced by other systems.

A full list and description of reinforcing and balancing loops, and a detailed integrated model displaying all variables are available in the Appendix.

[Insert Figure 1 here]

Figure 1: Causal loop diagram displaying an overview of the relationships between each subsystem in the model

Variables in blue are subsystems containing drivers of UPF production (subsystems 1-3), variables in green are environmental impact subsystems (subsystems 4-7). ‘R’ denotes reinforcing loops, ‘B’ denotes balancing loops. Polarity of relationships are not shown as there are both positive and negative polarities contained within the subsystems and reinforcing loops, see subsystem models for more details.

3.2 Subsystem 1: Commercial drivers of UPF systems

This subsystem focuses on commercial drivers. Four reinforcing loops were identified, all of which include the variable ‘*profitability*’, indicating that it is a primary driver of this subsystem. *Profitability* reflects the primacy of shareholders and the cost minimising and sales maximising tendencies of free market capitalism (Wood et al., 2021a; Wood et al., 2021b). With a sustainable financial model, *profitability* generates financial gains for shareholders and supports investments for ongoing growth (Figure 2). Depending on market conditions, this can enable the accumulation of *greater material resources and economic power* within food systems (Wood et al., 2021a). For example, corporations producing UPFs can use these accumulating resources to support *foreign direct investment* and the development of their global sourcing and distribution networks, and to grow through *mergers and acquisitions* of competitors (Hawkes, 2005; Wood et al., 2021b) (Figure 2). These strategies can result in *market concentration*, whereby fewer large companies own or influence a greater proportion of UPF product markets, thereby reducing *market competition* and maximising profit (Wood et al., 2021b). These are displayed in the reinforcing loops whereby increased economic power enables further economic gains (R2, R12 & R13, Figure 2).

Accumulating *material resources and economic power,* can further support *corporate political activities* intended to foster policy, regulatory and knowledge environments conducive to continuing market growth. These activities include lobbying policy-makers, funding scientific research for corporate benefit, and preferencing *public-private partnerships and self-regulation* over state-led food systems governance and command-and-control regulation (Clapp and Scrinis, 2017; Moodie et al., 2021). These are further described in the Appendix.

Reinforcing loop 13 displays that *corporate political activities* may also support *subsidies of agricultural inputs and commodities* used as UPF ingredients (Orden and Zulauf, 2015), which is enabled and reinforced via *profitability,* and the *economic power of the UPF industry* (Figure 2).

Reinforcing loop 1, which overlaps with subsystem 3, represents the intensive and sophisticated *marketing* techniques, including product design, branding and packaging, and advertising in massmedia and digital channels, which increase the *desirability of UPFs* and encourage *purchasing and consumption* (Bailey, 2016; Moran et al., 2019).

In addition to the system drivers describe above, other factors act to further encourage UPF purchasing and consumption. This includes *market competition* between food corporations, fast food chains and supermarkets which may increase pressure to maintain low *costs of final products* (Richards and Hamilton, 2006), and reinforce the reliance on low-cost commodity ingredients. A small variety of these commodity ingredients can be used to create an apparent diversity of UPF products, targeting different market segments.

Differentiating UPF system impacts from general food system impacts

We hypothesise that the above factors are more prominent in UPF systems compared with non-UPF systems. UPFs are often (but not exclusively) produced and sold by transnational organisations and therefore are associated with transnational corporate power consolidation and growth, as described above. However, more empirical evidence is needed to understand to what extent the political economy driving UPF production differs from non-UPFs.

[Insert Figure 2 here]

Figure 2: Causal loop diagram of Subsystem 1: Commercial drivers relevant to UPF systems

Figure 2 Legend: Black boxes and arrows indicate the supply chain, blue boxes and arrows are system drivers and grey arrows are used to denote links to other subsystems. 'R' denotes reinforcing loops, polarity of relationships are denoted by +/- next to the arrow head. Dotted lines indicate that the relationship was proposed (no existing empirical evidence), and solid lines denote that the evidence was established (supported by empirical evidence or reviews of empirical evidence). Reinforcing loops, balancing loops and connections (arrows) in grey are described in subsequent subsystems. Other figures display socio-cultural and biological drivers of UPF purchasing and consumption (Figure 3 & 4), climate change and air pollution impacts (Figure 5), land-related impacts (Figure 6), water use and aquatic impacts (Figure 7), loss and waste (Figure 8).

3.3 Subsystem 2: Socio-cultural drivers of UPF purchasing and consumption

Subsystem 2 displays the socio-cultural drivers of UPF purchasing and consumption (see Figure 3). Variables were grouped under five of the six pillars of food security (access, availability, stability, utilisation and agency) (HLPE, 2020). The sixth pillar, sustainability, is the focus of subsystems 4-7.

All reinforcing loops in this subsystem act by influencing consumers' *desirability for UPFs*. *Profitability,* successful *marketing* and *access to UPFs* were proposed to work together to increase *desirability of UPFs*, *purchasing and consumption*, creating reinforcing loops (R1, R14, Figure 3). Food policies and regulation could act to reduce these effects (Macari et al., 2019), potentially decreasing the profits and therefore economic power of the UPF industry (B1, Figure 3).

The *desirability of UPFs* may also be driven by their convenience, especially for individuals who lack food literacy skills needed to *utilise non-UPFs* (Chak Leung Lam and Adams, 2017). The *ability to utilise non-UPFs* may be further enabled or hindered through *agency* including self-efficacy, employment status, *time pressures*, family commitments and financial constraints (Chang et al., 2019; Contento et al., 2007; Davison et al., 2015; Jalambadani et al., 2017). This could be reinforced by ongoing *purchasing and consumption of UPFs,* which eliminates the need to learn to prepare meals and cuisines made from non-UPFs (R15, Figure 3).

Differentiating UPF system impacts from general food system impacts

While the relationships described above are not necessarily exclusive to UPFs, impacts may be more significant for these food products as they are often more accessible, available, easy to utilise and require little agency to consume them compared with non-UPFs (Chak Leung Lam and Adams, 2017; Chang et al., 2019; Contento et al., 2007; Davison et al., 2015; Jalambadani et al., 2017).

[Insert Figure 3 here]

Figure 3: Causal loop diagram of subsystem 2: Socio-cultural drivers relevant to UPF systems

Figure 3 Legend: Black boxes and arrows indicate the supply chain, blue boxes and arrows are system drivers and grey arrows are used to denote links to other subsystems. 'R' denotes reinforcing loops, polarity of relationships are denoted by +/- next to the arrow head. Dotted lines indicate that the relationship was proposed (no existing empirical evidence), and solid lines denote that the evidence was established (supported by empirical evidence or reviews of empirical evidence). Reinforcing loops, balancing loops and connections (arrows) in grey are described in subsequent subsystems. Other figures display the commercial drivers of UPF systems (Figure 2), biological drivers of UPF purchasing and consumption (Figure 3 & 4), climate change and air pollution impacts (Figure 5), land-related impacts (Figure 6), water use and aquatic impacts (Figure 7), loss and waste (Figure 8).

3.4 Subsystem 3: Biological drivers of UPF purchasing and consumption

This system displays changes in the composition of foods as they become ultra-processed, biological drivers of consumption and human health impacts (Figure 4).

While no new reinforcing loops were identified, *purchasing and consumption* of UPFs (which drives *profitability* and therefore encourages increased production of UPFs, see Subsystem 1), is likely promoted via biological drivers.

Differentiating UPF system impacts from general food system impacts

The majority of this subsystem is specific to UPFs. *Ultra-processing* enables changes in *nutrient composition* and *degradation of the food matrix,* which act to increase *palatability* and decrease *satiety* (Fardet et al., 2018). As a result, *palatability* (Almeida et al., 2018) and decreased *satiety* can promote *purchasing* and *overconsumption* (Hall et al., 2019). Beginning during early childhood, consumption of ultra-processed infant foods of homogenous flavours and textures may inhibit development of taste preferences associated with healthy eating habits throughout life (Foterek et al., 2015; García et al., 2013). The potentially *addictive* nature of UPFs, hypothesised to be driven by product design characteristics such as *palatability* (Schulte et al., 2015), may also play a role in encouraging excessive consumption of UPFs notably in adults and children who experience food addiction (Filgueiras et al., 2019; Pursey et al., 2015).

Also encompassed in this subsystem are the *adverse health outcomes* associated with UPF consumption and discussed extensively elsewhere (Elizabeth et al., 2020; Lane et al., 2021). Health impacts may occur directly due to over-consumption of UPFs (Matos et al., 2021) or indirectly through *dietary displacement of non-UPFs* (Martini et al., 2021).

[Insert Figure 4 here]

Figure 4: Causal loop diagram of Subsystem 3: Biological and biochemical drivers relevant to UPF systems

Figure 4 Legend: Black boxes and arrows indicate the supply chain, blue boxes and arrows are system drivers and grey arrows are used to denote links to other subsystems. 'R' denotes reinforcing loops, polarity of relationships are denoted by +/- next to the arrow head. Dashed lines denote that evidence for the relationship was emerging (inconclusive empirical evidence), and solid lines denote that the evidence was established (supported by empirical evidence or reviews of empirical evidence). Reinforcing loops, balancing loops and connections (arrows) in grey are described in subsequent subsystems. Other figures display the commercial drivers of UPF systems (Figure 2), socio-cultural drivers of UPF purchasing and consumption (Figure 3 & 4), climate change and air pollution impacts (Figure 5), land-related impacts (Figure 6), water use and aquatic impacts (Figure 7), loss and waste (Figure 8).

3.5 Subsystem 4: Climate change and air pollution impacts from ultra-processed food systems

Subsystem 4 examines the impact of UPF production on climate change and air pollution (Figure 5). This subsystem is not closed but rather provides an overview of the flow-on impacts related to climate change, because climate change affects a wide range of environmental systems (Figures 6-8). Therefore, we focus here on an overview of how climate change and air pollution interact with the subsequent environmental subsystems.

It was assumed by the lead authors and agreed by the participants that the energy used across the supply chain is predominantly produced by burning fossil fuels, because fossil fuels remain the dominant global energy source (Ritchie, 2020). *Energy created by burning fossil fuels* drives *air pollution* (Balasubramanian et al., 2021; Domingo et al., 2021) and *greenhouse gas emissions*, the major driver of *climate change* (IPCC, 2021) (Figure 5). *Fertiliser* and *pesticide use* also contribute to *climate change* as they are produced using fossil fuels, and fertiliser application is associated with nitrogen volatilisation (Shi et al., 2020).

Climate change has significant flow-on effects for elements in subsequent subsystems, including *land and soil degradation*, *changes in types and locations of pests* (IPCC, 2022), *biodiversity loss* (IPCC, 2021), *agrobiodiversity loss* (Fatima et al., 2020)*,* changes in *water scarcity* (IPCC, 2021) and *food loss and waste* (IPCC, 2022). For example, *climate change* may lead to *changes in types and locations of pests*, which may increase *pesticide use* in certain regions (see Subsystem 5). As a result, more *greenhouse gas* emissions may be released, which, if this occurs to a great enough extent, could worsen *climate change* (R5, Figure 5).

Finally, inputs used in agricultural production such as fertilisers and pesticides, as well as agricultural production processes such as field burning and livestock waste, contribute to *air pollution* (Balasubramanian et al., 2021; Domingo et al., 2021), which in turn have impacts on *human health* (Benka-Coker et al., 2020; Su et al., 2022).

Differentiating UPF system impacts from general food system impacts

Core to the difference between UPFs and non-UPFs within this subsystem is the assumption that UPFs are derived from large-scale industrial agricultural practices. Because wide use of fossil fuels throughout the food system can enable the production of cheap agricultural commodities (Fuje, 2019; Kaur et al., 2015), it follows that ultra-processing may be used to convert these commodities into profitable, palatable and marketable products (see subsystems 1-3). While it was generally assumed that UPFs are inherently reliant on industrial production systems, evidence to support this is needed and not all participants agreed on this assumption.

[Insert Figure 5 here]

Figure 5: Causal loop diagram of Subsystem 4: Climate change and air pollution relevant to UPF systems

Figure 5 Legend: Black boxes and arrows indicate the supply chain, blue boxes and arrows are system drivers, green boxes and arrows denote environmental drivers and outcomes, grey boxes indicate other system outcomes deemed relevant by participants and grey arrows denote links to other subsystems. ‘R’ denotes reinforcing loops, polarity of relationships are denoted by +/- next to the arrow head. All relationships in this subsystem were supported by empirical evidence, as denoted by the solid lines connecting variables. Relationships where polarity was dependent on the region are denoted with a question mark. Reinforcing loops, balancing loops and connections (arrows) in grey are described in subsequent subsystems. Other figures display commercial drivers of UPF systems (Figure 2), socio-cultural and biological drivers of UPF purchasing and consumption (Figure 3 & 4), land-related impacts (Figure 6), water use and aquatic impacts (Figure 7), loss and waste (Figure 8).

3.6 Subsystem 5: Land-related impacts from ultra-processed food systems

Subsystem 5 describes the land-related impacts resulting from UPF production (see Figure 6). While all stages of food production require land, participant discussions and existing studies have focused on agricultural production as the predominant driver of land-related impacts (Hadjikakou, 2017; Ridoutt et al., 2020; Willett et al., 2019).

Reinforcing loops were identified between *land and soil degradation* and *pesticide use*, *fertiliser use, agrobiodiversity loss* and *land scarcity* (R16-19, R21 Figure 6). Pesticide-related impacts on *agrobiodiversity loss* may be reinforced by changes in *types or locations of pests* and *pesticide use* (Isaac et al., 2021) (R20, Figure 6). Furthermore, as mentioned in subsystem 4, fertilisers release greenhouse gas emissions, driving climate change, which further degrades land and increases land scarcity, potentially leading to a vicious cycle of higher fertiliser demands (R4, Figure 6).

Also included in the model is the role of *land conversion* and *land and soil degradation* in increasing *land scarcity* (Jayasuriya, 2003). In theory, increased *fertiliser* and *pesticide use* could result in 'land-sparing', as less farmland is required to produce the same yield (IFA and UNEP, 2000; Popp et al., 2013). This is important as land sparing scenarios, where yields are increased through *fertiliser* and *pesticide use*, produce less *greenhouse gas emissions* than those released from *land conversion* in land sharing scenarios (Folberth et al., 2020). However, participants and previous literature have noted that high-yielding farms often expand, which may incentivise deforestation and subsequently increase *land scarcity* (Hertel et al., 2014). Thus, the question mark in the model highlights that, without the addition of more detailed causal pathways or quantitative data, the impacts described here are uncertain.

Differentiating UPF system impacts from general food system impacts

The relationships between agricultural-production practices and land-related impacts are not exclusive to UPFs. However, participants discussed that *ultra-processing* may exacerbate existing issues in the food system. Many UPFs rely on *agricultural production* of high-yield, low-cost ingredients*,* thus they may increase reliance on practices such as monoculture farming or intensive livestock production (Fardet and Rock, 2020), which could contribute to additional *land and soil degradation* (Olsson et al., 2019) (Figure 6). However*,* some features of this subsystem, e.g. *agrobiodiversity loss,* have been ongoing, independent, trends in agriculture (FAO, 2007), thus any impacts that may be caused by UPF production are additional to existing issues.

There are two reinforcing loops in this subsystem which relate specifically to UPFs. Participants proposed a reinforcing loop between *ultra-processing* and *agrobiodiversity loss*, as decreased variety of species may encourage creative processing methods to develop 'exciting' 'new' foods and UPFs may encourage reliance on fewer, cheap ingredients (Fardet and Rock, 2020) (R21, Figure 6). *Agrobiodiversity loss* also has flow-on impacts on *biodiversity loss* within neighbouring ecosystems

(FAO, 2019; Kremen and Miles, 2012). Changes in food supply diversity may also impact *food supply stability* (Thrupp, 2000) and *diet diversity* (Oduor et al., 2019). It is also plausible that ongoing production and consumption of UPFs could reduce diversity in the food system (R3, Figure 6).

[Insert Figure 6 here]

Figure 6: Causal loop diagram of Subsystem 5: Land-related impacts relevant to UPF systems

Figure 6 Legend: Black boxes and arrows indicate the supply chain, blue boxes and arrows are system drivers, green boxes and arrows denote environmental drivers and outcomes, grey boxes indicate other system outcomes deemed relevant by participants and grey arrows denote links to other subsystems. Dotted lines indicate that the relationship was proposed (no existing empirical evidence), and solid lines denote that the evidence was established (supported by empirical evidence or reviews of empirical evidence). 'R' denotes reinforcing loops, polarity of relationships are denoted by +/- next to the arrow head. Impacts which may increase or decrease are denoted with a question mark instead of a +/-. Reinforcing loops, balancing loops and connections (arrows) in grey are described in subsequent subsystems. Other figures display commercial drivers of UPF systems (Figure 2), socio-cultural and biological drivers of UPF purchasing and consumption (Figure 3 & 4), climate change and air pollution impacts (Figure 5), water use and aquatic impacts (Figure 7), loss and waste (Figure 8).

3.7 Subsystem 6: Water use and aquatic impacts from ultra-processed food systems

This subsystem investigates the impact of water used during UPF production and impacts of UPF systems on aquatic ecosystems (see Figure 7).

The reinforcing loops identified in this subsystem act together to impact *water scarcity, water quality* and *biodiversity loss*. In this model, water is used at most stages of production, which may lead to reduced availability of water in natural ecosystems, increasing *water scarcity* (Falkenmark, 2013). This is further impacted by *water quality*, as water resources that are polluted become less valuable, increasing *water scarcity* (Dabrowski et al., 2009). Conversely, *water scarcity* can impact *water quality*. For example, droughts are generally associated with poorer *water quality* due to a build-up of pollutants (Hrdinka et al., 2012). However, whether *water quality* increases when *water* *scarcity* decreases is uncertain and dependent on the region as higher rainfall can flush contaminants and beneficial substances, as well as introduce new contaminants into waterways (Hrdinka et al., 2012). This uncertainty is indicated by question marks in the model. Polarity could be specified if the model is adapted to contain detailed, context-specific causal pathways.

Increased *water scarcity* and decreased *water quality* can lead to *land and soil degradation, biodiversity loss* in aquatic and terrestrial ecosystems (Olsson et al., 2019) and *poor human health* due to contamination (Li, 2018). *Biodiversity loss* can impact *water scarcity* and *water quality* because native aquatic species often play a role in maintaining *water quality* (Worm et al., 2006) (see Appendix). These relationships can reinforce each other, driving increasing damage to ecosystems (see R6-8, Figure 7). Specifically, reinforcing loop (R8) shows how *water scarcity, land degradation*, *eutrophication* and *poor water quality* can act together to worsen environmental degradation (see figure 6).

Other components of this subsystem may worsen damage described above. For example, *fertilisers* and *pesticides* can have further impacts on *water quality* and *biodiversity loss* via *eutrophication* (Olsson et al., 2019) or *ecotoxicity* (Aktar et al., 2009; FAO, 2019).

Differentiating UPF system impacts from general food system impacts

While much of the above description is applicable to all foods, processing and ultra-processing can require substantial water inputs, depending on the product. A study analysing water used to produce ultra-processed meat alternatives found that processing accounted for 63% of product lifecycle water use (Fresán et al., 2019).

Additionally, impacts from fertilisers may be particularly relevant to UPFs as previous evidence suggests that ‘sweets, snacks and drinks’ (which are often UPFs) accounted for 42% of diet-related phosphorus use and 12% of diet-related nitrogen use in Sweden (Moberg et al., 2020). Overall further research is needed to determine if there are different mechanisms or larger impacts relating to water used for UPF production.

[Insert Figure 6 here]

Figure 7: Causal loop diagram of Subsystem 6: Water use and aquatic impacts relevant to UPF systems

Figure 7 Legend: Black boxes and arrows indicate the supply chain, green boxes and arrows denote environmental drivers and outcomes, grey boxes indicate other system outcomes deemed relevant by participants and grey arrows denote links to other subsystems. Solid lines denote that the evidence was established (supported by empirical evidence or reviews of empirical evidence). 'R' denotes reinforcing loops, polarity of relationships are denoted by +/- next to the arrow head. Impacts which may increase or decrease are denoted with a question mark, rather than a polarity such as +/-. Reinforcing loops, balancing loops and connections (arrows) in grey are described in subsequent subsystems. Other figures display commercial drivers of UPF systems (Figure 2), socio-cultural and biological drivers of UPF purchasing and consumption (Figure 3 & 4), climate change and air pollution impacts (Figure 5), land-related impacts (Figure 6), and loss and waste (Figure 8).

3.8 Subsystem 7: Loss and waste impacts from ultra-processed food systems

This subsystem describes the relationship between the production of UPFs and loss or waste of resources (see Figure 8).

One key driver of this subsystem is the assumption that *lost or wasted food* (which occurs at each supply chain stage (Bajželj et al., 2020)) may drive *agricultural production* to compensate for the *lost or wasted food* (de Gorter et al., 2021) (proposed link and R22, Figure 8). This results in *wasted food system resources*.

Linked with this concept are the bi-directional relationships whereby *time pressures* to reduce *food loss and waste* can be abated by *processing, ultra-processing* (Augustin et al., 2016) and *packaging* (Marsh and Bugusu, 2007) (B2-4, Figure 8). Balancing loop B5 indicates how *processing*, *ultra-*

processing and *packaging* lead to increased *food durability*, thereby decreasing *food loss and waste*. However, some level of *food loss and waste* still occurs as a result of these processes, as indicated by the reinforcing loops (R22-24, Figure 8). Additionally, valorisation (where by-products are processed or ultra-processed into food ingredients or products) may drive UPF production, as a UPF vessel may be required to carry the valorised ingredients (Capozzi et al., 2021) (see R19, R20, Figure 7).

Impacts from poorly handled waste may amplify impacts seen in previous subsystems, such as *biodiversity loss* (Azevedo-Santos et al., 2021), *poor water quality, land and soil degradation* (Chae and An, 2018), and *greenhouse gas emissions* (Scialabba et al., 2013; Tabata, 2013). These feed into reinforcing loops whereby more food is lost or wasted due to environmental events such as climate change (IPCC, 2022) or changes in pests (Delgado et al., 2021) (R9-11).

Differentiating UPF system impacts from general food system impacts

Impacts discussed above highlight that UPFs both cause and alleviate waste in the food system. One UPF-specific impact relates to UPFs driving *overconsumption* (Hall et al., 2019). *Overconsumption* may theoretically drive an oversupply of calories to some markets within the food system and represent a *waste of food system resources* which could otherwise be spared or re-routed to produce non-UPFs (Seferidi et al., 2020) (proposed relationship, Figure 8).

Also, *packaging* is inherent in UPF systems as UPFs are typically packaged, often in plastic. This contributes to UPFs waste-related impacts (Andrades et al., 2016), and may distinguish them from some non-UPFs, such as fresh foods. However, durable foods, such as UPFs, tend to be less wasted in households than perishable non-UPFs (Reynolds et al., 2016; Reynolds et al., 2015). Quantitative comparisons of the impact of UPF production and consumption on overconsumption, food loss and waste and packaging waste would help clarify whether UPFs are associated with more or less waste than non-UPFs.

[Insert Figure 8 here]

Figure 8: Causal loop diagram of Subsystem 7: Loss and waste impacts relevant to UPF systems

Figure 8 Legend: Dotted lines indicate that the relationship was proposed (no existing empirical evidence), and solid lines denote that the evidence was established (supported by empirical evidence or reviews of empirical evidence). Black boxes and arrows indicate the supply chain, blue boxes and arrows are system drivers, green boxes and arrows denote environmental drivers and outcomes, grey boxes indicate other system outcomes deemed relevant by participants and grey arrows denote links to other subsystems. 'R' denotes reinforcing loops, polarity of relationships are denoted by +/- next to the arrow head. Reinforcing loops, balancing loops and connections (arrows) in grey are described in subsequent subsystems. Other figures display commercial drivers of UPF systems (Figure 2), socio-cultural and biological drivers of UPF purchasing and consumption (Figure 3 & 4), climate change and air pollution impacts (Figure 5), land-related impacts (Figure 6), and water use and aquatic impacts (Figure 7).

3.9 Transitioning to a healthy and sustainable food system

Throughout the workshops, participants were prompted to discuss how the current UPF food system may differ from an idealised food system producing non-UPFs. Participants acknowledged that the production of non-UPFs can also cause environmental harm but re-iterated the importance of comparing the UPF-based system to a vision of a healthy and sustainable future food system. Therefore, the counterfactual was an idealised system producing non-UPFs, using environmentally sustainable production methods, adapted to the local environment. In this system, a variety of crops and livestock species would be farmed and bred for durability, flavour, nutrition and yield.

Determining the differences between the drivers and impacts within a UPF system compared with a healthy and sustainable food system was challenging in the absence of quantitative data. Variables that may be more prominent in a UPF system compared with an idealised food system are displayed in the Appendix. When asked to compare the impacts of UPF versus an idealised food system, participants often discussed potential trade-offs that could result from this transition. Some trade-offs are described in Table 1.

Table 1: Examples of trade-offs identified by participants which may occur when transitioning to an idealised food system

Trade-offs	Description
Energy use versus food system efficiency	UPFs can rely on high-energy inputs, but these energy inputs may enable efficiency, which may result in lowered energy demands at subsequent supply chain stages. For example, high energy demands for ultra-processing increase food durability, meaning energy-intense refrigerated transportation may not be required. It also could reduce the weight of the product through dehydration, or reducing bulk by converting grain to powder, which would further minimise transportation costs. Participants noted that in an idealised food system, energy inputs would need to be prioritised for foods that are essential for a healthy diet but that food system efficiency would need to be weighed against other environmental impacts from intense production processes, described previously in subsystems 4, 5 & 6.
Land sparing versus land sharing	Changing to less-intense production systems (e.g. pasture-raised livestock) may come at the cost of requiring more land to produce the same amount of foods. This may benefit agrobiodiversity but result in a loss of natural habitat for species living in the wider ecosystems (biodiversity loss), known broadly as the ‘land-sharing versus land-sparing debate’.
Diversity versus efficiency	More diverse agricultural systems may encourage a variety of non-UPFs (and thus discourage industrially produced and homogenous UPFs) but may result in efficiency losses due to time and cost pressures for farmers, relating to increased physical labour and management. For example, due to the need to manage a wider variety of pests and harvesting systems or to determine additional buyers for each new crop or livestock product.

Trade-offs	Description
Wasted food system resources versus food loss and waste	UPFs can be perceived to waste resources because the scarce resources used to produce them are being used to produce foods which are superfluous to human nutritional requirements, and often encourage overconsumption. However, the production and consumption of UPFs instead of non-UPFs (which may be more perishable) may contribute to reduced food loss and waste in the system due to their durability and ability to utilise waste-reduction processes such as valorisation (see Subsystem 7). Thus, any food system transitions which decrease UPF production should consider unintended increases in food loss and waste.
Food supply stability versus healthfulness	Improving the healthfulness of the food supply by decreasing access and availability of UPFs may result in negative impacts on food supply stability. For example, in emergencies where access to fresh food is limited. UPFs are easy to consume (no preparation or ‘tools’ are required) and safe (due to their long shelf lives). However, because these foods are not “…of appropriate quality…” (as per the definition of food security (FAO, 2006)), they may have a negative influence on food and nutrition security.
Prioritising sustainability and healthy outcomes versus cost	Utilising a range of sustainable practices, including nutrient cycling, regenerative agriculture and more localised supply chains (where beneficial), as well as farming and breeding a wide variety of crops and livestock species for durability, flavour, nutrition and yield would likely lead to substantial cost increases. Changes would need to be complemented with the development of a range of new technologies, practices, and regulations, to avoid negative impacts on livelihoods and food security.

Trade-offs	Description
Convenience versus healthfulness	Transitioning to healthy and sustainable food systems without accounting for convenient food products, may mean that those who are already time-poor and have limited cooking skills may be further disadvantaged. To account for this, food system transitions would need to consider accessibility to convenient non-UPF foods.

4. Discussion

Using group model building (GMB) and complemented with information from the peer-reviewed literature we developed a series of causal loop diagrams (CLDs) identifying drivers of the ultra-processed food (UPF) system and dynamic interactions with the environment.

Our approach to modelling impacts according to supply chain stages is supported by existing quantitative evidence showing significant variability between environmental impacts at each stage of food production (Crippa et al., 2021; Tubiello et al., 2021a; Tubiello et al., 2021b). The resulting model may be applied to guide the identification of system trade-offs, research activities and provide further insights for policy makers.

4.1 Identification of system trade-offs

This model highlights potential trade-offs associated with a reduction of ultra-processed foods (see examples in Table 1). While these trade-offs have been previously discussed in the peer-reviewed literature, the model can be used as a tool to enable further discussion of these trade-offs among researchers and policy-makers. For example, policies that reduce UPF accessibility should consider mitigating potential impacts on overall food access, particularly for those already experiencing food insecurity. Potential impacts for those with limited cooking skills or who are time-poor, or resource-poor would also need to be considered, due to the association between these factors and reliance on convenient UPFs, particularly among disadvantaged populations (Moran et al., 2019). Energy trade-offs should also be considered as industrial pre-cooking may be less energy intensive than individual home cooking (Scott et al., 2021), but these benefits are possible without ultra-processing (Davidou et al., 2022). Mitigating these risks is particularly important in the current climate of rising costs of living, which are disproportionately affecting already disadvantaged populations in the wake of the COVID pandemic and political unrest in key food-producing regions (Hawkes et al., 2022).

Food waste trade-offs may exist when transitioning from UPFs to a healthy and sustainable food system (see Table 1). Mitigation strategies could include campaigns to reduce household food waste (Aschemann-Witzel et al., 2017), and re-routing supply chain waste into animal feed (Truong et al., 2019) or biofuels (Pour and Makkawi, 2021), instead of UPF production. Time pressures in the food system would remain, however primary and secondary processing may alleviate some pressures relating to shelf-life (Augustin et al., 2016). For example, processing could be prioritised to extend shelf-life of nutrient dense and environmentally demanding, perishable products such as milk powders and small fish.

4.2 Potential policy implications

While further research is needed to understand local contexts and more detailed interactions, causal loop diagrams may be useful for policy design. Using policy to interrupt the reinforcing loops or affect variables with many flow-on effects may impact the quantity of UPFs produced by the food system and their subsequent environmental impacts. In this model, this includes variables such as the corporate political activity of the UPF industry and their economic power, low costs of the final product, access to UPFs, greenhouse gas emissions and climate change, land and soil degradation, fertiliser and pesticide use, food loss and waste, and packaging waste. Reducing the load on these systems through regulation may improve subsequent impacts such as overall production and consumption, air pollution, water quality issues, biodiversity and waste impacts. Economic impacts, such as price increases, could be added to the model and used to avoid unintended consequences of systems change. Further analyses of trade-offs and uncertainties, adapting the model to local contexts or specific food and beverage products, and adding delays to the model may help to anticipate policy resistance and pre-emptively propose solutions, and ensure recommendations are context specific.

4.3 Informing future research activities

This study could inform future quantitative analyses and qualitative models. While it was not the explicit purpose of this study, the GMB process is well-suited to identifying the key parameters and metrics to develop more comprehensive quantitative analyses of the food system (Laurenti et al., 2014; Werner, 2005). Using our model to identify relevant supply chain stages and variables for quantitative analyses may help overcome some of the challenges in quantifying the environmental impacts of UPFs discussed in the introduction. The model could also be used to interpret quantitative findings in the context of the broader food system.

The model could also be used to identify evidence gaps and research opportunities. The relationships denoted with dashed or dotted lines in Figures 1-7 (such as market competition and ultra-processing in Figure 1) have been proposed but, to the authors' knowledge, remain untested, or evidence is inconclusive. Many of these highlighted relationships are key to understanding complexities in the food system and inform solutions, including policies.

Finally, the model and accompanying description presented in this paper could be used as a basis for modelling studies. To adapt this model to a healthy and sustainable food system, supply chain stages, variables and relationships could be removed or added using the editable modelling file provided in the Appendix. For example, variables could be added to enable a comparison with alternative production systems, to understand impacts on workers' or animal rights, or to further unpack complex interactions summarised in our model. A quantitative model could also better differentiate between UPF and non-UPF impacts.

4.4 Limitations

The model developed in this study aimed to capture the key relationships between the UPF system and the natural environment, including all system drivers. While we aimed to retain as much detail as possible, the system does not capture every known or possible impact, which is an unavoidable disadvantage of mapping complex food systems (von Braun et al., 2021). Many issues discussed in the text are relevant to the food system generally, not just UPFs. While this made it difficult to differentiate impacts from UPFs, it also makes the model more applicable to future studies on other types of food. Included variables, relationships and how they were framed was ultimately subjective, and dependent on the diversity of knowledge of modellers. To reduce the risk of bias, we grounded the model in existing evidence, ensured that the participant size was appropriate for the method (Rouwette and Vennix, 2020), and validated all participant suggestions using existing peer-reviewed evidence. However, some evidence may have been missed in the searching process, as only the first 100 results were searched. In addition, we did not review the strength of the evidence according to pre-established methods such as GRADE (Guyatt et al., 2008), but instead used a simplified ranking method to distinguish between peer-reviewed empirical evidence, and proposed associations between variables. We also recruited participants from a wide range of countries, however, not all world regions were captured.

While there are many uses of the CLD described in this paper, there are limitations in its application. Because it is a qualitative model, the strength of the relationships between variables, magnitude of impacts, and correlation between environmental metrics were not tested. The model does not account for region-specific impacts. The model is also not product or location specific. To analyse a particular product, especially those with complex or unusual supply chains, such as cellular meat, additional components and considerations may be required.

5. Conclusion

Our findings indicate multiple avenues through which UPFs impact the environment, driven by commercial, biological and social influences on production and consumption, with multiple interactions between and within subsystems. While some impacts are likely to be more prominent in a UPF-based food system, there was some difficulty differentiating impacts from UPFs compared with non-UPFs. Quantitative research is needed to better differentiate the impacts of UPFs compared with non-UPFs. This work also identifies policy-relevant trade-offs which would need to be mitigated if UPF production or consumption is reduced. Future improvements to the model could include adding delays, including more disciplines, categorising evidence using pre-established grading criteria, adapting it to local contexts or adapting the model to non-UPFs.

The model highlights research gaps and could be used to guide choices on supply chain stages, and environmental impacts relevant to UPFs for quantitative studies, as well as to provide a guide for interpreting quantitative findings in the context of complex and dynamic food systems.

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