Article

Market pathways to food systems transformation toward healthy and equitable diets through convergent innovation

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Achieving food system transformation requires a deep understanding of the market mechanisms that underpin both the social benefits and the externalities of modern development. We examine how market dynamics affect the production and consumption of healthy and equitable diets in North America. Using causal loop diagramming, we show how three market feedback processes (industry capabilities, consumer category considerations, and systems and institutions) both constrain and enable food system transformation. Through behavioral-dynamic computational modeling, we demonstrate the ineffectiveness of isolated social or commercial interventions to achieve equitable access to nutritious foods across populations of varying socioeconomic statuses. Rather, self-sustaining transformations at scale require convergent innovations that bridge individual and collective action across typically siloed sectors, to achieve alignment between commercial, social, and environmental goals and activities. We discuss how this simulation-based analytical framework can inform policy for food system transformation, whether at the local, national, or global level.

Transforming food systems is essential to addressing global health, social, and environmental challenges targeted by the Sustainable Development Goals (SDGs)[1,2]. Various approaches have opened pathways to achieve this transformation, each focusing on specific transformational dimensions, including livelihoods, poverty, and equity[3]; diets, nutrition, food security, and health[4]; and biodiversity, environment, and natural resources preservation such as regenerative farming practices[5,6]. For instance, regenerative farming practices focus on improving soil health[6] and sequestering carbon to reduce greenhouse gas emissions[7] through crop rotation and reduced tillage. Other efforts leverage digital support through data analytics and artificial intelligence to increase efficiency in farm production and food processing[6]. Some emphasize culturally responsive food systems transformation to ensure that they reflect local contexts and cultural diversity[8,9]. Many initiatives call for governance-centric strategies, recognizing the importance of principles that guide knowledge, policy, and action toward resilient, safe, and just food systems[10,11]. In turn, continuous learning frameworks emphasize the role of adaptability[12] and education and knowledge sharing[11] in driving sustainable transformations.

While each of these approaches and frameworks taps into crucial elements of food systems transformation, daunting challenges still lie ahead, considering the baseline conditions prevailing around the world, especially regarding equitable consumption of high nutritious food[13]. Food systems are complex natural and social systems which tend to resist isolated pathway-altering efforts, as they are replete with positive feedback relations that can engage in vicious cycles producing

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lock-in into established practices[3,14,15]. However, with sufficient suitable systemic efforts, these same feedback loops can come to operate in a virtuous rather than in a vicious direction. Such dynamics, driven by market formation and industrialization, have been core to early food-systems development to current baseline conditions, shaping farm and food production, distribution, and consumption and driving societal benefits and externalities[16]. Hence, food market mechanisms are particularly pivotal in transforming food systems, including those toward healthier and more equitable diets. Understanding these market mechanisms and transformation pathways is essential for devising effective systemic interventions and policies that can lead to lasting positive changes at scale within food systems. Furthermore, the broad scope and distributed control of the food value chain under-score the need for instruments that not only align goals but also sup-port coordinated actions, including but going beyond individual interests of the different stakeholders from governments, the private sector, and civil society[1,17].

This paper analyzes the problem of how market mechanisms affect the dynamics of equitable healthy food system transformations. Using an inductive multi-stage process (see section "Methods"), we demonstrate a comprehensive approach for analyzing and guiding market transformation pathways. We illustrate this through a stylized analysis of transformation from low-nutrition to high-nutrition food (LN-HN food) for low- and high-socioeconomic status (low-high-SES— representing here respectively the bottom and top 50%) populations, within the North American context. (For a list of definitions of all acronyms used, see Supplementary Information (SI) S.1.) Using exist-ing knowledge of market formation mechanisms, we first identified three key market-level feedback processes—industry capabilities, consumer category consideration, and systems & institutions—that shape the development of food market infrastructure. Next, convert-ing this characterization into a computational model, we examined the system's responses to diverse interventions through simulation. Engaging these individually and jointly through simulation, we com-pare their impacts against a no-intervention baseline in terms of scale, equity, and health-oriented induced innovation. We show that strong and lasting equitable impacts leverage the synergistic effects across the market infrastructure dimensions, implying the importance of comprehensive, coordinated individual and collective action among for-profit (FP) producers, social entrepreneurs, not-for-profits (NFPs), governments, consumers, and other intermediaries. Identifying mar-ket mechanisms that both resist and enable food system change, this work advances knowledge on science and society efforts toward SDGs by explaining persistent challenges rooted in market dynamics and providing a framework to point to transformation obstacles and identify high-impact interventions for sustainable change at scale.

Results

A first key output of our analysis was a conceptual model of healthy food market transformation pathways derived by combining stake-holder engagement with literature reviews and causal loop diagramming (see section "Methods", Stages 1–3). This served as the basis for developing the behaviorally dynamic computational model repre-senting how the system evolves as different actors respond to observed changes within the system, such as producers adjusting resources or consumers adapting consumption. The conceptual model also guided the creation of the baseline and intervention sce-narios and helped interpret simulation results. Therefore, before dis-cussing the baseline and simulated intervention scenarios, we first lay out this conceptual model.

Conceptual model

Within established markets, firms satisfy well-understood consumer demand and preferences by assuring product availability and perfor-mance along different attribute dimensions[18,19]. In food markets, taste, satiety, and convenience are key motivational forces, typically traded off by consumers with nutritional quality[20] and cost factors[21,22], and all central in the firm's innovation efforts. Consumers also respond to extrinsic factors impacting product positioning and visibility at market access points: on-label claims and promotions[23,24], product size assortments[25], product variety[26], shelf presentation and packaging[27], and shelf-life[28] (see Fig. 1, "Consumer Attribute Sensitivity"). Firms can improve performance along these attributes by exploiting existing intra-organizational capabilities—the ability to convert resources into doing something valuable[29]. Present consumption provides both financial resources and information for ongoing product and manu-facturing practice improvements along selected attributes[28] (Fig. 1, loop R0, "Product Sales").

Transforming markets in fundamental ways—as is needed for equitable healthy food consumption—requires development of new market infrastructure[30]. Market infrastructure comprises material, sociocognitive, and commercial elements such as agreed-upon pro-duct categories, consumption practices, product prototypes, norms of exchange, or technology standards. These elements shape consumer demand, guide and stabilize structured at-scale exchange within markets, enable ongoing investment, and facilitate collaboration and knowledge diffusion and sharing among producers and business partners within supply chains, networks, and alliances, and through this enable the innovative efforts in a given direction[31,32]. If limited or no market infrastructure supporting a product category exists, efforts are needed for its development.

We define the market infrastructure here along three dimensions, representing respectively the supply- and demand-related elements[31], and the public and private constituencies supporting their interaction[30,33]: (i) Industry Capabilities, (ii) Category Consideration, and (iii) Systems & Institutions. Industry Capabilities refer to the knowledge, resources, and organizing structures that are shared at the industry level and facilitate the ability to produce and market a variety of appealing products within given food product categories at low cost and high volume. Category Consideration comprises beliefs, values, norms, status, and agreed-upon practices pertaining to the food pro-duct categories within different population segments. Systems & Institutions encompass the social, economic, informational, and phy-sical systems that support, facilitate, and help coordinate market exchanges and product distribution and retailing of the product categories.

We represent each market infrastructure dimension as stocks (Fig. 1, boxes linking to "Category Market Infrastructure"), empha-sizing their accumulative nature and initial inertia in building, changing, or dismantling each of these components. Their dis-aggregation (stacked boxes) reflects the differentiated support they offer across food product categories (symbol c) and for their con-sumption across population segments (symbol s), and firm-level heterogeneity (symbol f). For example, firms differ in their will-ingness to undertake (potentially risky) action toward societally beneficial innovation[34]. Such heterogeneity may therefore imply presence of ambitious early movers but can also imply presence of free-rider problems[31].

Building new Industry Capabilities to support healthy food consumption requires reconfiguring routinized activities and devel-oping shared knowledge bases about prototype products, best practice harvesting or production processes, technology and quality standards, exchange networks, etc. Whereas shared industry cap-abilities may sometimes develop over time as spillovers from pro-ducers' private knowledge-building efforts, generally this involves explicit coordination efforts and establishment of relationships[32,35]. Either process accumulates the stocks of industry capabilities through Research & Development (R&D) efforts (Fig. 1, "R&D Improvement" flowing into the "Industry Capabilities" stock). These decisions and actions form a reinforcing (positive) feedback loop as
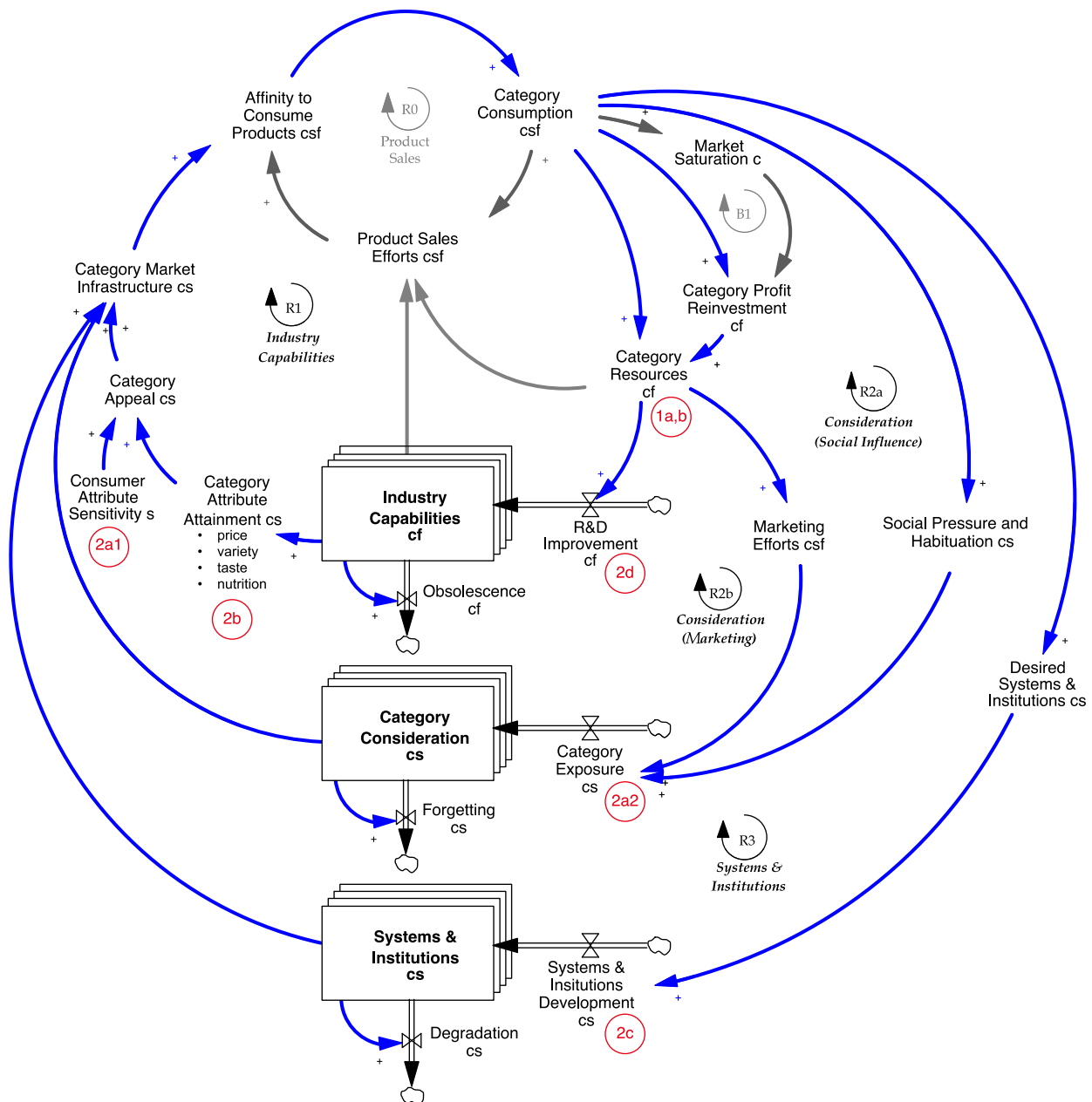
Fig. 1 | Conceptual model of food market transformation, and locus of interventions. Indices: healthiness of food category $c \in \{HN, LN\}$; demographic segment $s \in \{low - SES, high - SES\}$; firm type $f \in \{1, 2\}$. Boxes represent stocks; arrows with valves represent flows. A stock is the accumulation of the difference between its inflows and outflows. A plus or minus at the arrowhead indicates the polarity of the causal relationship. A plus sign denotes that an increase in the independent variable causes the dependent variable to increase (and a decrease causes a decrease), ceteris paribus; that is, $X \rightarrow_+ Y$ implies $\partial Y / \partial X > 0$ and $X \rightarrow_- Y$ implies $\partial Y / \partial X < 0$[14]. Red-circled numbers indicate the locus of direct influence of interventions discussed in the paper, with numbers referring to those used in the paper (see Fig. 2 and Table 2).

industry capability accumulation facilitates product introductions, revenues, and further reinvestments within the forming category (Fig. 1, loop R1, "Industry Capabilities"). Industry capabilities stabilize due to limits in demand expansion and diminishing returns from learning-curve trajectories[36], also suppressing reinvestment (Fig. 1, loop B1, "Market Saturation").

Onset and development of Consumer Consideration of alternative product categories—irrespective of attractiveness of available options—requires consumer awareness, familiarity, and knowledge[37,38]. Through social exposure and other influence processes, consumers form collective expectations of common product dimensions[39]. As new products become increasingly similar and recognizable, categorical prototypes emerge (refs. 40,41; Fig. 1, "Category Exposure"

flowing the "Category Consideration" stock). Social influence from peers occurs through direct observation of others' behavior, information exchange, or transmission of social norms[21,42,43], and is amplified through media attention[44] and habituation and sensitization[45,46]. Thus, social influence about a product category grows with its consumption (Fig. 1, link from "Category Consumption" to "Social Pressure and Habituation"), closing a positive feedback loop (Fig. 1, loop R2a, "Consideration (Social Influence)"). Producers (and others) strengthen this process by educating consumers and shaping their understanding of or attention to new categories[47,48]. As firms dedicate available resources to product advertisement, on-product label claims, product promotions, and product size assortments[23,24] depending on their assessment of returns, compared to those for R&D investments and for

other product categories, this forms another positive feedback loop (Fig. 1, loop R2b, "Consideration (Marketing)").

Creating social and commercial Systems & Institutions supporting industry and consumer affinity for healthy product categories and equitable diet requires efforts ranging from those leading to favorable regulation, to formation of distribution and logistics networks, to the shaping norms of exchange across organizations and communities[33,49]. In the food context, these efforts enable speedy transport of food from farms, processing plants, and manufacturing centers to different retail outlets (e.g., supermarkets, convenience stores, or farmers markets) and food service locations (e.g., restaurants, cafeterias, catered operations), or allow outlets to be equipped in accessible places (e.g., with refrigeration, storage, and preparation facilities), particularly critical for fresh perishable products. Activities also involve the development of supply-chain-level collaboration structures, understandings about logistics, and cultures falling outside the direct scope of industry capabilities. Such efforts may, for example, reduce supply chain risks or support circularity[50]. Food supply not only interlinks multiple sectors (e.g., agriculture, fertilizing, processing, transport and distribution, retailing) but is also deeply embedded within a larger system of structures (e.g., the economic system, government regulation, incentive programs, tariff schedules, technology standards) that incentivizes and constrains firm and market behavior. Without such elements in place in support of product categories, consumers have difficulty accessing these products, have less exposure to them and, thus, would be less likely to consider them[51]. Systems and institutions development may require efforts by social entrepreneurs, FP and NFP market actors, and other intermediaries, as well as by government players (Fig. 1, "Systems & Institutions Development" flowing into the stock). These efforts increase as actors respond to and anticipate growth in supply and demand of the categories they support, completing the final positive feedback loop (Fig. 1, loop R3, "Systems & Institutions").

In summary, a core challenge for many food systems transformations involves navigating a system of interdependent feedback relations connecting market infrastructure dimensions. The more distinct the alternative product categories are from the established products and consumer practices and habits, the more and more diversified the efforts and supporting actors are required, and the greater the importance of explicit coordination among different actors. Collective action problems can easily emerge, and compound if current demand is absent or future demand is uncertain, or when many firms may benefit from market infrastructure development. Finally, market transformation may be constrained by inertia, yielding large time delays between market-building efforts and results[52–54]. Such switching inertia is particularly relevant when markets move toward health- and sustainability-oriented product categories, which tend to have initially contested valuation and require lifestyle-changing efforts, whereas the status quo is rooted in strong habit formation and highly routinized behavior[55–57].

Baseline assumptions
The baseline scenario for the analysis reflects consumption patterns prevalent in Western societies[15], i.e., dominated by processed food, high in motivational value but low in nutritional value[58], particularly for low-SES communities[51]. We differentiate high versus low nutritious food, $c \in \{HN, LN\}$, and high-SES versus low-SES populations (s). We derive the baseline from four empirical regularities (Table 1 with examples; see Methods, Stage 4 for the approach; see SI S.2 for additional examples). First, the as-is market infrastructure is less developed for HN food than for LN food, across all three dimensions (Table 1, "Market Infrastructure State," compare HN versus LN). For example, conventional practices of retail outlets better support sales of processed shelf-stable food than fresh perishable ones[59,60]. Second, the as-is market infrastructure better facilitates HN food production and

consumption for high-SES than for low-SES populations (Table 1, "Market Infrastructure State," compare high-SES versus low-SES). For example, industry's convenient, but high-cost, functional food capabilities serve high-end consumers better than low-end consumers[61]. Third and fourth, intrinsic differences between the product categories or in the sensitivities to product attribute states across populations strengthen any asymmetries in market infrastructure effects (Table 1, "Product Category Attribute State," compare LN versus HN, and "Consumer Product Category Attribute Sensitivity," for the four attributes we represent in this paper: price, variety, taste, and nutrition). Fundamentally, such differences are malleable and shaped by socio-behavioral processes. For example, observations of greater susceptibility to fatty/sweet motivational qualities within low-SES (versus high-SES) populations of LN foods can be attributed to habituation, reinforced by biological, addiction-like mechanisms[62,63]. However, changing this is a slow process and depends on the market transformation itself, biasing as-is choices against HN food. Our baseline scenario characterizes these differences respectively through the "normal" values for attribute states and consumer sensitivities to price and nutrition between high-SES and low-SES populations.

Computational model and simulation
We next converted the conceptual model (Fig. 1) into a computational model (Methods, Stage 5; for the model description and equations, the quantification of the baseline and interventions, and model download and replication instructions, see SI S.3-S.8). Simulating the operationalized baseline assumptions of Table 1 (see SI Table S.7) yields an organically sustained equilibrium favoring LN food consumption, particularly within low-SES population segments, with suppressed industry investments, demand, and market infrastructure for HN food and healthy diets, which then further perpetuates the dominance of LN food consumption (SI Table S.7 "Category Consumption" conform Table 1, "Category Consumption").

Intervention scenarios
We examined the effectiveness of intervention scenarios representing various at-scale efforts toward equitable healthy diets undertaken by different actors, including FP producers, non-producers, NFPs, and governments (Fig. 2), acting upon distinct parts of the system (Fig. 1, circled numbers). We differentiate two types of producer firms $f \in (\{1, 2\})$. They are identical in capabilities and profit-seeking behavior and have equal initial market shares across product categories and population segments. However, only type 1 firms, representing those more willing to undertake prosocial action, partake in FP interventions. (Both types may respond by adjusting resource allocations based on perceived changes in returns on investment.) We analyzed market dynamics following either a five-year-lasting temporary or permanent intervention and compared outcomes to the baseline. Results of the simulated intervention scenarios are summarized in Table 2, showing for each (from left to right), compared to the baseline, the average increase in fractional HN food consumption ("scaling"), the fraction of the HN food consumption gap between high-SES and low-SES populations closed ("equity"), and change in HN food R&D investment by firms ("innovation"), for the year 2028 (1 year after expiration of temporary interventions, "2028") and for the post-intervention new equilibrium state ("equilibrium"). Also shown ("No FB," in italic), for reference, the final equilibrium results with the feedbacks involving product category exposure affecting Category Consideration and product category consumption affecting Systems & Institutions deactivated (see SI S.5 for technical details). In discussing results, we illustrate three interventions in more detail (Table 2, Figure numbers indicated in column 1).

First, FP actors can unilaterally spur healthier food consumption by targeting higher-end niche markets[64–66], as Nestlé's 20-25B

Table 1 | Characterization of baseline scenario

Variable	Healthy (HN)		Low-Health (LN)		Selected examples[a]
	Low-SES	High-SES	Low-SES	High-SES	
Market infrastructure state (Baseline equilibrium values)					
Industry Capabilities[b]	L	ML	H	MH	Industry capabilities evolved to favor highly processed, lower-cost[134], higher motivational quality[21] LN food[50,58]. Product costing systems are ill-equipped to stimulate HN food consumption in low-SES populations compared to high-SES populations[61].
Category consideration[b]	L	ML	H	MH	Exposure through advertising and promotions of highly processed LN foods far outweigh those for healthy food[22,135]. Low-SES populations tend to get greater exposure to low-healthy food[62].
Systems & institutions[b]	L	ML	H	MH	Schools, retail outlets, etc. facilitating greater availability and accessibility of LN versus HN food[59,60]. Within low-SES urban areas, corner stores dominate, offering limited healthy food options[62,136], with LN food having larger shelf-life and lower refrigeration needs[61].
Product category attribute state (Baseline equilibrium/parameter values)					
Price	M		L		LN foods tend to be cheaper to produce[137,138]
Variety	M		H		LN food characteristics tend to allow greater variety in choice[139]
Taste	M		H		LN foods tend to be more processed, saltier, sweeter, fattier, and perceived to be tastier[20]
Nutrition	H		L		True by definition
Consumer product category attribute sensitivity (Baseline parameter values)					
Price	H	L	See left		Low-SES populations' greater budget constraints makes them more price sensitive[61]
Variety	M	M			No basis for variation
Taste	M	M			No basis for variation
Nutrition	L	H			Greater strains on low-SES populations' time budgets on food preparation[57]
Consumption (Baseline equilibrium values)					
Category Consumption[b]	L	ML	H	MH	See main text[51,93,134]

Characterization of baseline values for key conceptualized state variables and parameters (Fig. 1) for HN versus LN food consumption across high-SES and low-SES populations, based on empirical observations in the literature.

H high, M medium, L low.

[a]See SI S.2 for additional examples.

[b]Variables can be found directly in conceptual model (Fig. 1).
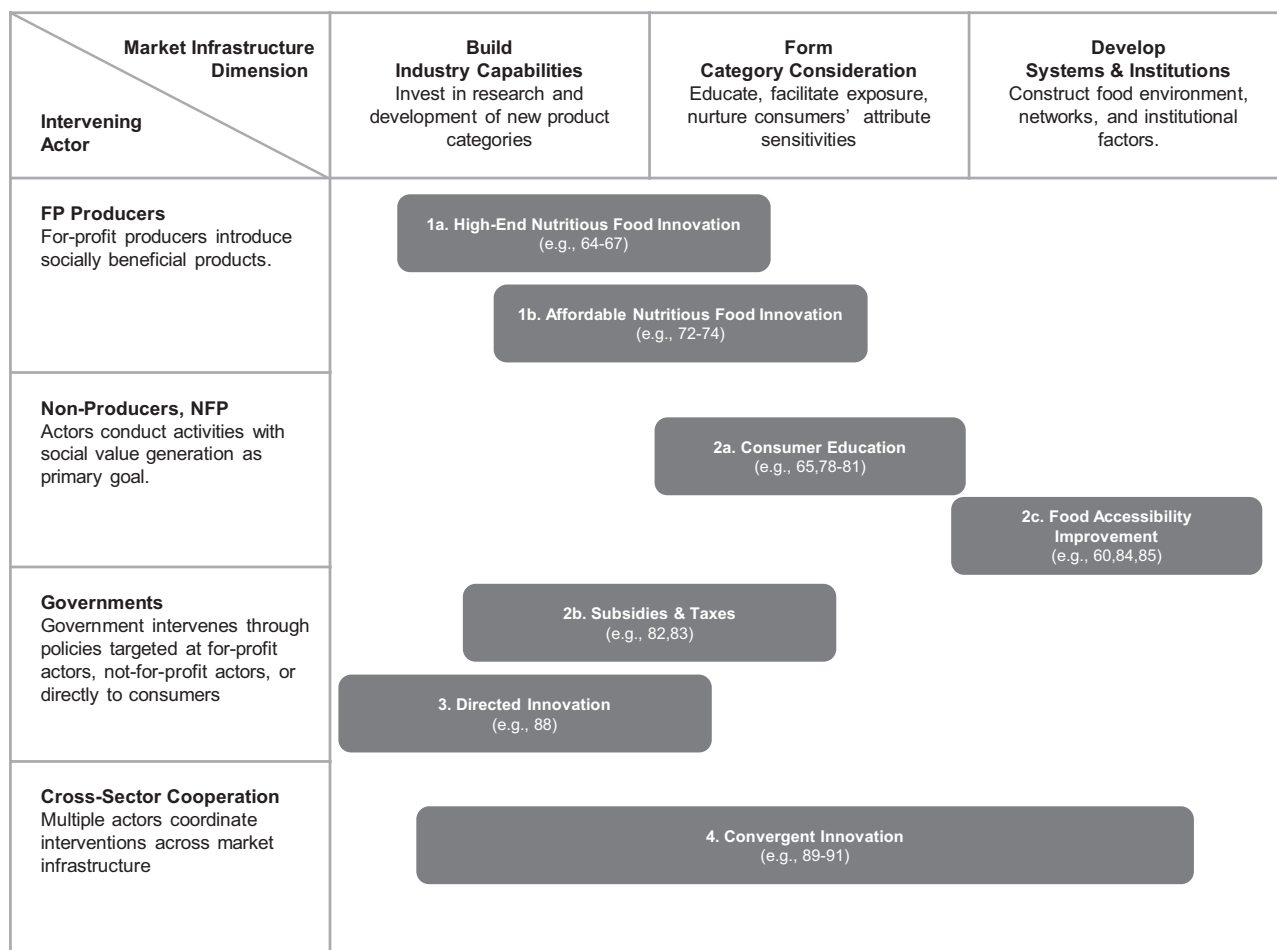
Fig. 2 | Simulated interventions by actor type and activities related to market infrastructure dimensions. (See SI Table S8 for scenario details.).

investment to boost sales of high Health Star Rated products[67], or entrants like Beyond Meat introducing plant-based meat alternatives. Figure 3 (thick red lines) shows the simulated market dynamics of "High-End Nutritious Food Innovations" (Intervention 1a), following one-off upfront investment raising capabilities for high-nutrition, -taste, and -price, products, supported by a temporary marketing campaign ($f = 1$). These efforts increase HN food appeal and consumption within high-SES populations (Fig. 3d and a: gray markers 1 and 2). Growing demand helps in turn build category consideration, as more and more consumers become exposed through peer influence and improve availability as retailers are increasingly willing to display these products (Fig. 3b, c: 3 and Fig. 1: loops R2a, R2b, and R3). Demand growth also stimulates ongoing HN food reinvestments beyond the initial shock, and through that further growth in consumption of still-expensive HN food among high-SES populations (Fig. 3d and a: 4 and Fig. 1: loop R1). However, for the low-SES populations, having greater price-sensitivity and with consideration of and access to HN food remaining low, demand does not grow (see Fig. 3: 5). Therefore, the HN food equity gap increases considerably (Table 2, Intervention 1a). Such differentiated demand response induces firms to increasingly favor improving taste over cost, further exacerbating the gap. The simulation of this intervention highlights that whereas high-end-oriented efforts induce longer-term product improvements and demand growth[68–70], hoped-for "trickling down" toward low-SES populations is difficult because of a lack of low-SES market infrastructure (e.g. ref. 72).

Alternatively, through social innovation efforts[72,73], firms can target HN food directly at mainstream/low-SES populations. For example, Campbell Canada developed an affordable "complete meal ready-to-

eat" soup specifically to address the needs of low-income populations[74]. Simulations of "Affordable Nutritious Food Innovations" Intervention 1b) using one-off large-scale capability investments ($f = 1$) for lower cost of and improved access to HN food, traded off with taste, show limited effectiveness in closing the gap (Table 2, Intervention 1b). Beyond lacking market infrastructure constraining initial demand responses, lower profit margins suppress reinvestment and necessary improvement in appeal, together constraining demand growth for both low-SES and high-SES populations (Fig. 3: thin blue lines). These results indicate that social innovation efforts, whether initiated by corporations like Campbell (whose efforts stalled) or by social entrepreneurs[75,76], cannot easily achieve high access and appeal necessary for scaled-up affordable healthy food consumption[77].

Results also illustrate the challenge of achieving at-scale impact through efforts to reduce barriers to equitable healthy diet uptake by nationwide governments, NFPs, or non-producing firms (Table 2, Interventions 2a-2c). Simulated efforts range from campaigns to increase attention to nutrition or consumer consideration of HN food categories within low-SES populations (Interventions 2a1 and 2a2[65,78–81]); price incentives, by imposing LN food taxes or HN food subsidies (Interventions 2b1 and 2b2[82,83]); or, improving food accessibility for low-SES populations (Intervention 2c[60,84,85]). All these interventions improve HN food consumption, particularly among low-SES populations, reducing the HN food consumption gap. For example, in response to Nutritious Food Exposure Campaigns (Intervention 2a2), low-SES populations increase HN food category consideration, inducing HN food demand (Fig. 4a, b: 1). However, whereas producers respond by increasing R&D efforts somewhat, this is mostly in

Table 2 | Numerical summary of simulated intervention results

Intervention	"Scale" HN food share			"Equity" HN food equity gap change[a]			"Innovation" HN food R&D change[b]		
Time of Measurement	2028	Equilibrium	*No FB*[c]	2028	Equilibrium	*No FB*	2028	Equilibrium	*No FB*
Baseline	0.378	0.378	*0.378*	0.00	0.00	*0.00*	0.00	0.00	*0.00*
Producer interventions									
1a: High-end innovation (Fig. 3)	0.386	0.403	*0.383*	0.12	0.23	*0.09*	0.03	0.06	*0.01*
1b: Affordable innovation (Fig. 3)	0.384	0.396	*0.382*	−0.01	−0.01	*−0.01*	0.01	0.03	*−0.01*
1ab: 1a + 1b	0.392	0.423	*0.388*	0.11	0.23	*0.08*	0.04	0.09	*0.00*
Non-Producer, NFP, government interventions									
2a1: Nutritious food education	0.389	0.415	*0.386*	−0.12	−0.19	*−0.08*	0.02	0.10	*0.02*
2a2: Nutritious food exposure [d](Fig.4)	0.384	0.397	*0.382*	−0.07	−0.10	*−0.05*	0.02	0.07	*0.03*
2b1: Low-nutrition food taxes [d]	0.387	0.409	*0.385*	−0.05	−0.07	*−0.03*	0.02	0.08	*0.02*
2b2: Nutritious food subsidies [d]	0.384	0.401	*0.383*	−0.08	−0.12	*−0.05*	0.01	0.07	*0.02*
2c: Nutritious food accessibility Efforts	0.386	0.422	*0.381*	−0.10	−0.24	*−0.03*	0.01	0.12	*0.01*
2 d: Directed innovation	0.404	0.432	*0.389*	0.04	0.05	*0.01*	0.57	0.15	*0.03*
Convergent innovation interventions									
3:[d]2a1 + 2c + 2 d (Fig.5)	0.438	0.524	*0.401*	−0.30	−0.45	*−0.10*	0.69	0.40	*0.06*
3a:[d]3 + 1a	0.446	0.552	*0.407*	−0.19	−0.25	*−0.02*	0.72	0.48	*0.07*
3b:[d]3 + 1b	0.444	0.546	*0.405*	−0.32	−0.49	*−0.11*	0.68	0.42	*0.05*
3ab:[d]3 + 1a + 1b	0.452	0.576	*0.412*	−0.21	−0.29	*−0.03*	0.70	0.50	*0.06*
3all:[e] 3 + 1a + 1b + (2a2 + 2b1 + 2b2)	0.463	0.649	*0.429*	−0.32	−0.64	*−0.16*	0.71	0.75	*0.13*

[a]Relative change in the difference of the HN food consumption share between high-SES and low-SES populations.
[b]Fractional increase in average firm R&D investment in HN food.
[c] Columns in italics ("*No FB*") report counterfactual "no feedback" outcomes. Their simulations are identical to those for "Equilibrium" except that the feedbacks involving product category exposure affecting Category Consideration and product category consumption affecting Systems & Institutions have been deactivated.
[d]Includes also temporary, 5-year-lasting, 2a2 + 2b1 + 2b2 campaigns.
[e]Includes permanent 2a2 + 2b1 + 2b2 campaigns.

substitution for now less-needed marketing efforts (Fig. 4c: 2). Furthermore, effects of exposure campaigns, if not maintained, are transient. In such cases, the reinforcing feedback loops eventually drive the system back toward the low-HN food equilibrium (Fig. 4: 3, compare thick lines (temporary intervention) and thin lines (permanent intervention)). The same holds true for financial interventions (2b1 and 2b2). Altogether, whereas NFP and government efforts are potentially important, in isolation, they have limited capacity to invert the market infrastructure feedback loops that lock the market into low capabilities and limited consideration of healthy food choices (see SI S.6, Fig. S1 for additional graphs). Empirical evidence supports this notion. For example, within low-SES populations, there have been observations of low demand responsiveness to price reductions[86]—despite budget constraints—or healthy eating programs[87], attributed to limited availability of complementary factors such as access, information, and relevant cooking skills.

A different type of government-driven intervention involves directed innovation[88], aiming to help shift innovation and production toward HN food pathways by stimulating (discouraging) use of desirable (undesirable) inputs or practices and leveraging new synergies across the entire value-chain system. Simulating such a shift, through a one-off permanent and industry-wide capability shock plus temporary productivity improvements for HN food attributes, induces subsequent innovation. Over time, investments improve HN food attractiveness and consumption, somewhat stimulating improvements in systems and institutions and category consideration, leading to further firm investment in capabilities for HN food production (Table 2, Intervention 2d, and SI S.6, Fig. S2 for graphs).

Scenarios 3 combine multiple interventions that each by themselves cannot achieve impact across the three output metrics. The notion of aligning efforts for social and industry goals and value creation is consistent with those of "convergent innovation" (CI[89,90]), aiming to link science, technologies, and processes from different disciplines and sectors[91]. Figure 5 shows how addressing all three market infrastructure dimensions of HN food (through directed innovation, food accessibility increase, and nutritious food education programs, aided by temporary campaigns in nutritious food exposure and food subsidies and taxes) induces strong, lasting, and equitable impacts (Table 2, Intervention 3). HN food appeal experiences a substantial boost during the policy period as firms, perceiving opportunities from changing consumption and productivity, respond by aggressively investing in R&D for healthy foods (Fig. 5d: 1). Furthermore, benefits extend to low-SES populations (Fig. 5a: 2) and persist after the policy intervention ends (Fig. 5a: 3). These strong, lasting impacts result from the synergistic effects across the market infrastructure dimensions, as well as from the accumulative nature of their improvements, also driving ongoing HN food R&D investment (Fig. 5: 4). With greater low-SES responsiveness, investments also include lower-cost HN food. By organically shifting firms' day-to-day orientation and efforts toward HN food innovation, CI interventions not only increase HN food consumption but also considerably reduce the gap between high- and low-SES populations. Scale grows when firms individually also focus on High-End Innovation initiatives (Intervention 3a). Both scale and equity further improve when combining affordable healthy innovation efforts (Intervention 3ab). Under an extreme intervention scenario with temporary campaigns—on nutritious food
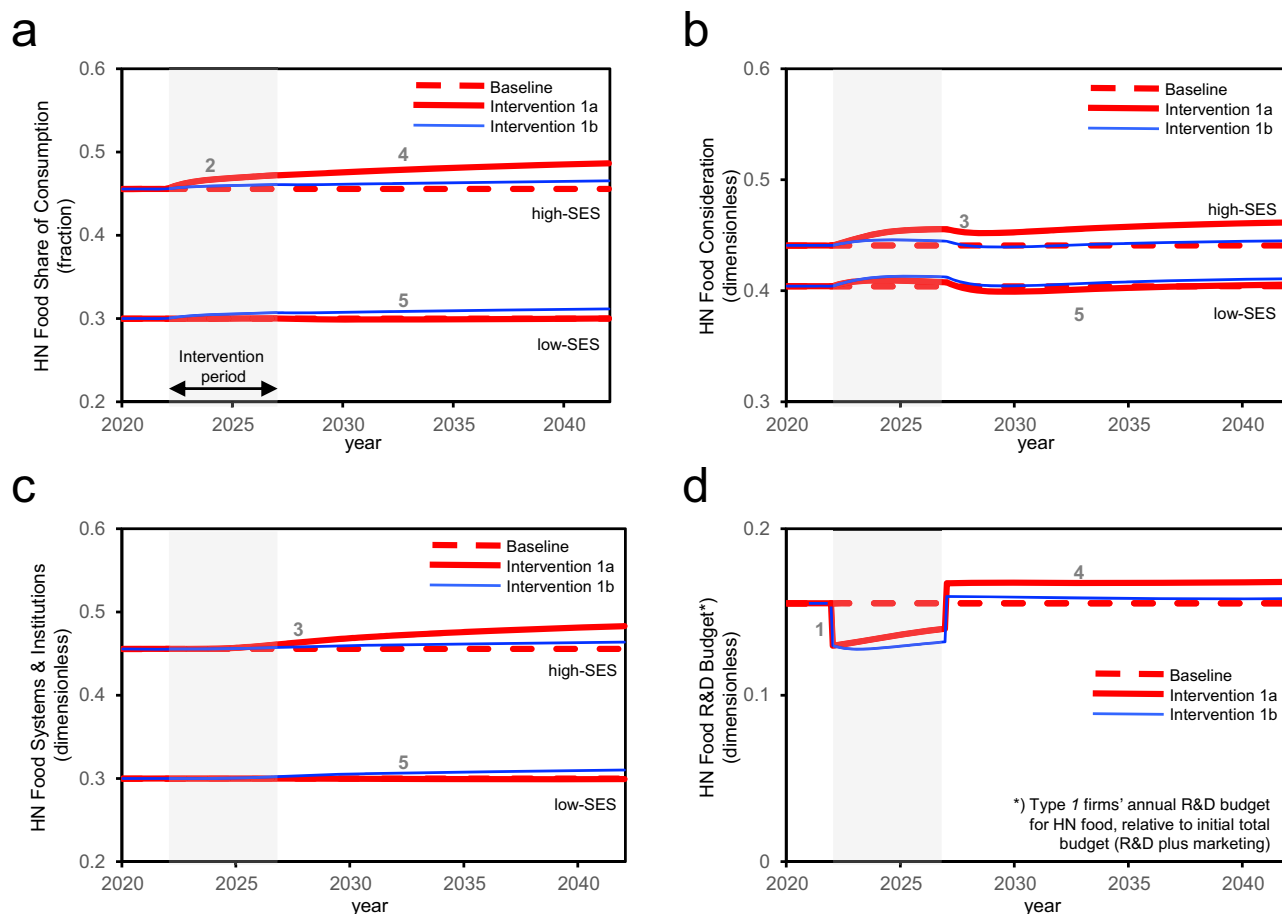
Fig. 3 | Dynamics of High-End Innovation (Intervention 1a, thick red line) and Affordable Innovation (Intervention 1b, thin blue line) for Nutritious Food. **a** HN Food Share of Consumption. **b** HN Food Consideration. **c** HN Food Systems & Institutions. **d** HN Food R&D Budget (type 1 firms, relative to initial total budget (R&D plus marketing)). For both initiatives. Type $f=1$ firms make an upfront, one-off R&D investment, leading to a positive step-change (starting 2022) in respectively HN food taste and nutrition, trading this off with HN food cost (Intervention 1a), and HN food cost and nutrition, trading this off with HN food taste (Intervention 1b). Both initiatives are accompanied by a HN food marketing campaign (2022-2027). Firms repay upfront investments between 2022 and 2027, subtracting this from their overall R&D and marketing budget. Note: Vertical scales are kept identical across figures where possible, to facilitate comparison. (See SI Table S8 for scenario details.) Gray number markers are referred to in sequence within the main text.

exposure, LN food taxes, and HN food subsidies—made permanent, all outputs ("Scale," "Equity," and "Innovation") considerably improve further (Intervention 3all).

Finally, comparing each intervention scenario with one in which market infrastructure feedbacks are absent (Table 2, compare "Equilibrium" with "No FB" (italic) columns) shows that all interventions benefit to some degree from endogenous market infrastructure improvements (for all but three "Equity" outputs, "Equilibrium" results are superior to "No FB" results). However, for CI these improvements are markedly greater than for the others, highlighting its capacity to leverage synergies across the market infrastructure dynamics.

Discussion

Food systems are pivotal in addressing global health, well-being, and sustainability issues but still face daunting challenges in ensuring equitable healthy food at scale. Our analysis highlights that large-scale food systems changes require market transformations[31] that involve complex system-level feedback dynamics and are hindered by strong lock-in effects[3,15]. Central to achieving sustainable, equitable, and scaled-up production and consumption of healthy diets is therefore ambitious individual and collective action involving diverse stakeholders—producers, consumers, social entrepreneurs, not-for-profits, governments, and intermediaries. Collaborative cross-sector approaches that consider these market transformation dynamics are key to

creating aligned incentives for ongoing innovation, reducing acceptance barriers, increasing consideration to overcome the inertial forces from a lack of initial market infrastructure, and pushing socially responsible activities from niche to mainstream. Domains beyond agrifood with well-established knowledge about creating, mapping, and maintaining cooperative networks, such as supply chain collaboration[92], can offer important lessons, for example about critical success factors such as trust building, technology and information sharing, and actor willingness to change[92–95]. Yet the fundamental market transformations that are needed, and the number and diversity of actors involved, also indicate considerably greater and different challenges[31,76,96].

Our analysis highlights the unsustainable divide between human, environmental, and economic health due to entrenched roles, responsibilities, and institutional arrangements within market structures[91]. With an increasingly populated world, excessive resource depletion, and inequalities, more and more goods provided through the market must be seen as semi-public[71,97] rather than just private. Yet, whereas societal value creation, aiming to correct problems of poverty, education, environment, or health, tend to be at odds with organizational value capture of capitalist systems, other pathways are possible[98], as our analysis illustrates. Such pathways require ambitious synergy-oriented policies—e.g., expanding grants, new coopetition models, and research funding—supporting purposive and directional
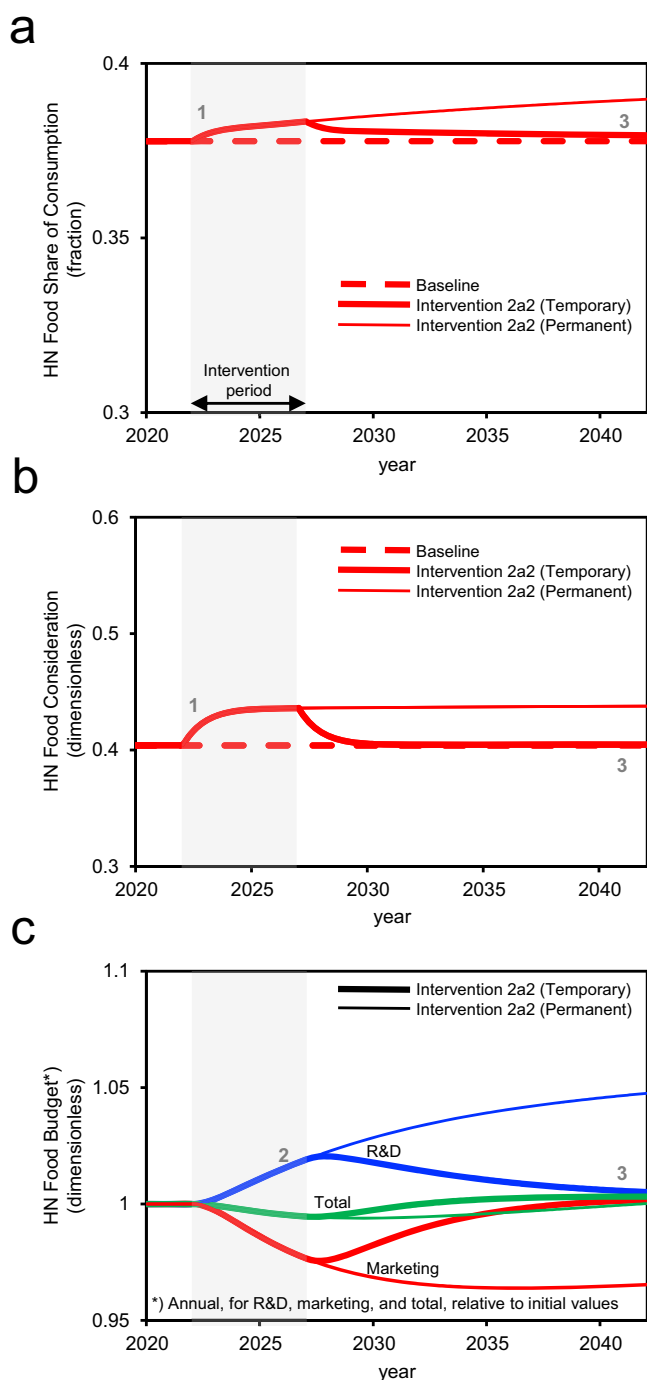
Fig. 4 | Dynamics of Nutritious Food Exposure Programs (Intervention 2a2). **a** HN Food Share of Consumption. **b** HN Food Consideration. **c** HN Food Budget (Annual, for R&D, marketing, and total, relative to initial values). For this initiative, governments or NFPs develop programs to increase HN Product Category Exposure among low-SES populations. Simulated initiatives start in 2022 and end in 2027 (thick line, temporary) or continue (thin line, permanent). Note: The vertical scale of HN food consumption (top left) differs from other figures to highlight details. (See SI Table S8 for scenario details.) Gray number markers are referred to in sequence within the main text.

research and innovation in the healthy food sector and considering all dimensions of the market infrastructure and its dynamic nature.

Achieving convergence of economic goals with environmental and social targets—from the global level to local communities—requires, however, more than leveraging operational and technological synergies. Transformations also depend on alignment of values[11,99],

requiring that the private sector serves as more than an engine for economic growth[88,91,100,101] and value-creation efforts that are more inclusively defined and shared across actors[102], including but not limited to FP organizations. This also includes shared orientations toward a resilient value chain, with an ability to withstand food supply shocks and guarantee food safety[50,103]. Necessary efforts go well beyond traditional corporate social responsibility (CSR) practices or campaigns and contrast sharply with the dominant situation in which societal benefits are on the periphery of an organization's radar[104] and with organizations carefully navigating often conflicting pressures from different stakeholders[105,106]. Success requires rethinking and addressing deeply rooted problems within conventional innovation systems that have fueled powerful economic growth and social progress worldwide since the onset of the first industrial revolution. Whereas the movement of reformulating organizational purposes is in motion[107,108], such reorientations that decouple risks from real action on social and environmental issues are challenging[109].

Results from the market pathways analysis also illustrate the critical role of non-industry actors through public-private interactions. These actors must guide the processes that enable societal value creation and sufficient firm value capture, by helping create a level playing field, shift norms and expectations, and spur creativity. Thus, more public-private interactions are critical, including forums bringing together actors on healthy diet production and consumption and fostering engagement in whole-of-society partnerships[110] and lasting partnerships[111,112]. Consumer behavior is also key, considering the importance of peer-influence-based mobilization. Consumers, especially those with means, can be leaders in lifestyle changes beyond simple product choices, including revised food purchasing, preparation, and reduced consumption. All together, our framework underscores that achieving sustainable and equitable food consumption requires substantial behavioral changes at all levels of society. Beyond just technological innovation, success demands transformations across individual (lifestyles and livelihoods), professional (mindsets, skills, practices), organizational (business models, practices, and supply chains), and systemic (policy, political economy, culture) levels. Solutions must therefore encompass cross-disciplinary collaborations involving diverse sectors and jurisdictions.

The focus on nutritious food for all in the North American context served as an illustrative, and stylized, test bed. More fine-grained analysis of specific critical transformation problems—be they nutritious food and equitable healthy diets; whole-of-chain food production and consumption including food circularity, freshness, and waste; or food safety; or their intersections—can naturally utilize this approach of market mechanisms analysis. Depending on the problem articulation, such analysis may include explicit representation of key elements of the food system, from consumers to retailing to feedstock and land use. This approach also applies to regions of the world at different stages of modern development. In fact, a key mindset change is needed in moving away from the first-industrial-revolution models of development, which still view agriculture as a steppingstone to industrialization and trade, to a fourth-industrial-revolution model that takes transition from traditional to modern agriculture as entry point for building resilient communities and cities[91]. The former models have led to a clear rural-urban divide in Western countries' economic and social structures and tend to continue doing so as traditional societies in Africa, Asia, and South America embrace modernity[16]. Recent investments and policies promoting agriculture-based local, regional, and intracontinental development, particularly in Africa, are encouraging. However, given the rapid pace at which human-made development is moving toward the planetary boundaries, it is evident that the market mechanisms driving agrifood system transformations must be adjusted and integrated with those of other social and economic sectors to achieve cohesive outcomes.
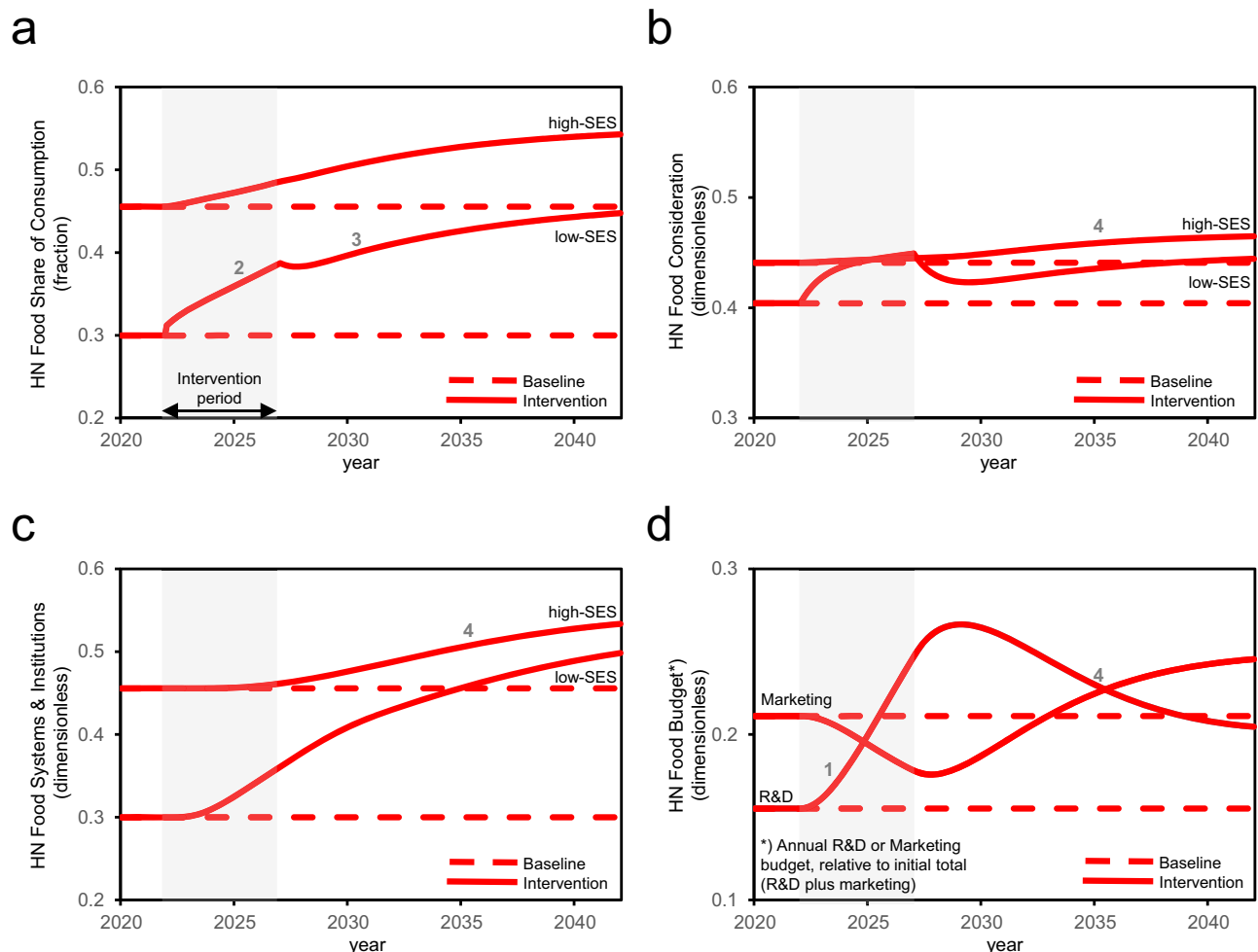
Fig. 5 | Dynamics of convergent innovation (Intervention 3). a HN Food Share of Consumption. **b** HN Food Consideration. **c** HN Food Systems & Institutions. **d** HN Food R&D Budget (Annual R&D or Marketing budget, relative to initial total (R&D plus marketing)). The basic CI scenario 3 combines interventions 2a1, 2c, and 2 d plus includes temporary, 5-year, 2a2 + 2b1 + 2b2 campaigns. (See SI Table S8 for scenario details.) Gray number markers are referred to in sequence within the main text.

It is important to acknowledge limitations of the assumptions underlying the current analysis. More research is needed to understand the optimal form, scope, and duration of convergent innovation efforts and alignment necessary for different food-types system transformation problems. This may also include, for example, consideration of interfirm dynamics including first-mover or free-rider advantages, perverse side effects resulting from convergence efforts, such as power concentrating in a small number of corporations, media intermediaries, or foundations, or individuals[75], or government or firm impositions to act. Furthermore, besides a broad applicability, the dynamically complex nature of transformation pathways also implies that specific mechanisms, dynamics, and intervention effectiveness can vary considerably across contexts. For example, coordinated efforts are most crucial in low-SES areas to invest in and develop underdeveloped market infrastructure. However, cultural and economic factors can, in some settings, exacerbate persistent consumption patterns within targeted areas. It's also crucial to explore how emerging alternative business visions and other societal shifts, like digital transformation, can be leveraged to drive agrifood sector innovation or to identify potential obstacles from powerful market actors.

In terms of methodology, this paper deployed system dynamics tools to examine stylized relationships involving distinct actors connected within the food market system. Refining, strengthening, and testing the proposed framework requires more empirical, including spatio-temporally based, research. Participative approaches can provide a framework for eliciting and sharing knowledge of the complex systems of food production-consumption across actors[113]. Computational models, well-grounded in empirics, using aggregate and disaggregated (compartment- or agent-based) architectures, can provide specific policy guidance and powerful new learning on food transformation. Learning environments grounded in such approaches can educate decision-makers and the broader population, as has been shown for climate action[114].

In conclusion, the challenges and solutions in our food systems are closely tied to how market systems and their actors shape food production, processing, distribution, preparation, and consumption. To transform food systems, research is needed to help society move beyond the Western industrial paradigm toward a convergence economy that integrates healthy eating with economic goals, fostering human and planetary health along with sustained, inclusive prosperity. This research offers a framework for identifying pathways toward large-scale market transformation. However, further studies are required in different global contexts to test and refine these concepts and computational models. By building a solid, evidence-based framework, we can guide market mechanisms and promote healthier, more equitable eating habits that align with Earth's resources.

Methods

We initiated this paper by building upon earlier conceptual work we had done on convergent innovation motivating the need for dynamic modeling approaches[89,115]. Realizing the underrepresentation of market mechanisms, here we undertook to develop a general framework that integrated market formation theory into convergent innovation to advance both conceptual and operational specification of market pathways, focusing on the problem of equitable nutritious food for all.

Five-stage research process

To develop our integrative dynamic framework and model for food market transformations, our study involved five stages. The initial three stages resemble the process of inductive theory-building[116], well-suited for understanding phenomena within complex social, economic, and institutional contexts[117]. Others have followed these stages using causal loop diagraming and subsequent theory-building[118].

Stage 1: Extensive examination, over multiple years, of the phenomenon of transformation challenges of food markets toward equitable healthy food.

Stage 2: Identification of conceptual elements, developed around the notion of market infrastructure and its various dimensions.

Stage 3: Development of an integrated conceptual model of challenges of healthy food market transformations using causal loop diagraming.

Stage 4: Development of a baseline and intervention scenarios for transformations toward equitable healthy food and diets at scale.

Stage 5: Development of a computational model and analysis of dynamics of and interventions for equitable healthy food transformations.

Stage 1: Examining and understanding the phenomenon and empirical context

The first stage involved extensive examination, over multiple years, of the phenomenon of transformation challenges of food markets toward equitable healthy food. As part of this stage, three of the co-authors conducted an in-depth literature review and engaged with stakeholders as part of a broader set of grants/mandates on food-systems transformation challenges, particularly for the Canadian / North American context but also including Europe and Asia. Consultations bore on the dynamics and main bottlenecks of food system change, specifying important market mechanisms, and compiling failure and success cases. To gain insight on the role as well as value created with and for the various stakeholders and to understand how these saw themselves as part of transformation efforts, the authors engaged with stakeholders from various organizations (for-profit, not-for-profit, and governments) and consulted with health, food, and commerce/trade experts through workshops to study healthy food transformations in diverse contexts. For example, following the UN declaration of 2016 as the International Year of Pulses, on-invitation only work sessions and public workshops were iteratively held over in Quebec, other Canadian provinces (Ontario, Manitoba, Saskatchewan, Nova Scotia), and in India, a primary importer of Canadian agrifood commodities. Two of the authors—one as organizer, one as frequent participant—engaged a worldwide network of stakeholders, including farmer, aggregator, distributor, processor, logistic, and retailer enterprises and the policymakers and investors / funding agencies at local, state/regional, national, and global levels that orchestrate food demand-and-supply conditions and contexts. This enabled us to accumulate real-world experience cases, and feedback from experts. Later, we continued to use similar workshop sessions to obtain feedback on our conceptualization and, after that, our model scenarios.

Stage 2: Providing theoretical underpinnings: market infrastructure for market transformations

As our understanding of market mechanisms developed, we turned to literature on market transformation. At this time, theory on market formation started to develop around market infrastructure and associated collective action problems[30,31]. Applying this concept to the food market formation problem helped us condense and conceptualize the many market mechanisms at an appropriate level, understand what constructs to use, and identify gaps in our representation of mechanisms. The literature emphasized major challenges to market infrastructure development that we deemed relevant to the food context, including: resource deployment, investment, and commitment from diverse market- and non-market actors involved[30]; absence of established market infrastructure creating uncertainty, leading to hesitancy among actors to take action[31]; biased decision-making within organizations and industries favoring long-established patterns and conventional practices and technologies versus commitments to new market infrastructure[33,52,54]; and limited sense of control for individual firms because multiple distinct inchoate elements needed[31]. Based on the empirical exploration (Stage 1), we also recognized the central role of collective action—how modifying or building new market infrastructure requires collective action across distinct market actors—for-profit and not-for-profit firms, firms, governments, and civil society—each controlling different elements[33,100,119]. Importantly, as had become also clear from our workshops, these actors are either unfamiliar with one another or tend to focus on competitive interactions. Finally, in early forming markets, government action may be important. However, governments may be hesitant to provide impositions when there is no existing market. And, if they do act, their actions may not align with those from industry[31,120]. Together these points illustrated that one can gain analytical traction from deploying the market formation theory as a basis for our food-systems transformation framework.

Stage 3: Developing a conceptual model of equitable healthy food market transformations

From the literature and engagement process, we formulated the mechanisms that enable and constrain market transformation, which we centered on the buildup of market infrastructure along the respective dimensions. To map these, given the circularity of relations, we used causal loop diagraming techniques and computational modeling and simulation. Causal loop diagrams are powerful tools for analyzing problems having multidirectional and circular relationships. They have been widely used in organizational and market research[118,121,122]. We followed standard mapping practices[14]. By combining conceptual elements and data from the specific context and the theories of market formation, we identified the three main causal linkages. The outcome was a well-grounded causal loop diagram (Fig. 1) that captures the dynamics of market transformations, with a specific focus on the healthy food context.

Stage 4: Developing a baseline and intervention scenarios

We next articulated a baseline scenario—providing an internally consistent explanation for how the meso-level interactions among distinct actors' decision-making on healthy food production and consumption combined to create macro-level dynamics. From this, we outlined scenarios involving distinct interventions for further exploration. First, as part of a larger project, we mapped out existing nutritious food consumption practices and access availability of the population by socioeconomic status, within the Province of Quebec. These efforts have been documented in different papers[123–126]. Main data and sources included for this are: (i) weekly product sales volume and unit prices (2008–2013), covering all products (by Universal Product Codes (UPCs)) within sixteen food and drink categories (including candy, regular and diet carbonated soft drinks, chocolate, cold and hot cereals, energy drinks, frozen juice, fruit, yogurts), by location (Canadian Forward Sortation Areas (FSA) and/or postal codes) and store type (grocery, convenience, healthy outlet, or supermarkets) [from the Nielsen Scantrack point-of-sales database]; (ii) calories, sugar, fat, and

per serving [the 2010 Canadian Nutrient File] that we matched to the UPCs; (iii) product label data on newly launched consumer-packaged goods, covering product claims, ingredients, nutritional information, packaging, and launch price [Product Launch Analytics (PLA) database (Datamonitor)]; and (iv) demographic data (2006 and 2016) [Canadian census across Quebec].

Socioeconomic status differentiates population segments by their access to financial, educational, social, and health resources. We used the neighborhood socioeconomic and household characteristics as proxy for individual socioeconomic and household characteristics. Representative FSAs for low-SES and high-SES populations were selected based on the following neighborhood socioeconomic characteristics: (i) Population density; (ii) Median family income; (iii) Proportion of the population aged 15 years and over that was employed; and (iv) Proportion of the population aged 15 years and over with post-secondary education. Splitting the population halfway into 50% low-SES and 50% high-SES, we matched consumption and access characteristics and demographics by postal code. We used this to characterize the healthy food consumption in low-SES and high-SES populations and availability of healthy food stores. Results were triangulated with literature findings, which we further used as sources for attribute-level characterizations (Table 1 and Table S7).

We then used the literature and empirical-oriented workshops (Stage 1) to identify types of interventions and articulate and develop different intervention scenarios (overview in Fig. 2, details in Table S8, columns 1 and 2).

Stage 5: Development of a computational model and simulation-based analysis

Given the dynamic complexity of the problem, our upfront goal had been to develop scenario analysis using computational modeling. Simulation is a powerful method for sharply specifying and extending existing conceptualizations and theory[127] and is particularly powerful for producing insights when the problem is longitudinal, nonlinear, or processual[128], as is the case here. We set out to operationalize a model as close as possible to the conceptual model (Fig. 1). Doing this required a focus on modeling how actors evaluate and adjust their actions behaviorally and endogenously over time, in response to changes they observe within the system (e.g., producers adjusting their investments in response to changes in accessibility or in consumer consideration of product categories, through increase in relative perceived marginal returns; or, consumers altering their consumption choices following changes in social exposure to products). To develop these notions, we used compartment (differential equation) modeling using the standard system dynamics practice and principles, used for such dynamic behavioral modeling[14,129]. For this we also built on a more aggregate and narrower-scoped model involving consumer-producer interactions[115].

The core equations necessary to understand the model that we developed and used for the analysis follow here. (Download instructions of the full model follow below.)

Market share σ_{cfp} of food category c by firms f within population segment p depends on consumers' relative affinity A_{cfp} with food category-related products:

$$\sigma_{cfp} = \frac{A_{cfp}}{\sum_{c'f'} A_{c'f'p}}. \tag{1}$$

Consumer affinity for consuming products within a product category increases with intrinsic, industry capability-based valuation A_{cfp}^i, as well as with the propensity to consume the category (Category Consideration) PtC_{cfp} and the state of Systems & Institutions I_{cp}

(cf. [130]):

$$A_{cfp} = PtC_{cfp}{}^{\alpha^p} I_{cp}{}^{\alpha^i} A_{cfp}^i, \tag{2}$$

where affinity to consume A_{cfp} attains the intrinsic economic utility-based valuation A_{cfp}^i when both PtC_{cfp} and I_{cp} equal 1, and equals 0 when one of them equals 0. The parameters α^p and α^i are weights indicating the relative importance of, respectively, propensity to consume the category and the development of systems and institutions.

Population-level intrinsic affinity follows the classic logit-choice utility structure valid under irr extreme value distribution of unobserved consumer preferences[14]. Following this, $A_{cfp}^i = \exp(u_{cfp})$, with individual-averaged utility u_{cfp} summing over the influence of l attributes, each depending on the effective attribute value a_{cfl}, and attribute-related consumer elasticity of demand β_l (consumer sensitivity to attribute change):

$$u_{cfp} = \sum_l \beta_l \left(a_{cfl} - 1 \right). \tag{3}$$

A category's effective attribute value a_{cfp} improves with the firm's attribute-specific capabilities CA_{cfl} (Industry Capabilities), under diminishing returns, following standard learning-curve theory and empirics[35,131]. Then: $a_{cfl} = a_{0,cl}(CA_{cfl}/CA_0)^{\eta^r}$ with learning-curve exponent $0 \le \eta^r \le 1$ and a_{cfl} attaining the reference attribute value $a_{0,cl}$ when capabilities equal a reference value CA_0.

Attribute-specific capabilities CA_{cfl} accumulate as resource budgets b_{cfl} are being allocated to improve the attribute l of category c by firm f, on the productivity of knowledge accumulation g, when resources equal the normal accumulation b_0. In addition, firms and categories benefit from scale economies, which are a function of total servings sales s_{cf}. Parameter λ^b [0,1] moderates the relative importance of resources (versus scale economies). Finally, firm capabilities decay exponentially (first order delay; 14), at capability decay time τ_c, indicating that, with time, previous research and development become obsolete as requirements change, competitive environments change, or consumer tastes change.

$$\frac{dCA_{cfl}}{dt} = g^0 \left(\frac{b_{cfl}}{b^0} \right)^{\lambda_b} \left(\frac{s_{cf}}{s^0} \right)^{1-\lambda_b} - \frac{CA_{cfl}}{\tau^c}. \tag{4}$$

Firms allocate resource budgets b_{cfl} behaviorally (cf. [14,129,132]). That is, they allocate resources based on expected returns from reinvestment into differing food categories. We assume they follow a hierarchical budget allocation structure[133]. Thus, firms first decide on allocation between food marketing efforts (improving consumer consideration) and R&D (improving products along relevant attributes). Next, given this, they distribute resources between HN and LN food categories, and subsequently, R&D resources among the different attributes (improving utility). Thus, for example, the R&D budget b_{cfl} for an attribute l depends on the total investment b_f by firm f, the total share σ_{cf} going to category c, and, within that budget constraint, the share σ_{cf}^R dedicated to R&D (rather than to marketing) and, within that budget constraint, the share σ_{cfl} going to attribute l (rather than to other attributes). Thus, $b_{cfl} = \sigma_{cfl} \sigma_{cf}^R \sigma_{cf} b_f$. Second, firms adjust budgets incrementally and smoothly[14]. Thus, for example, the share of the total resources b_{cf} for the category c going to R&D, σ_{cf}^R, adjusts to its indicated level σ_{cf}^R. Third, firms adjust budget shares at each level responding to their perceived marginal benefits, comparing this to those from other allocations. For example, in deciding to allocate resources between marketing and R&D, the indicated share is the result of the relative desired budget, where superscript R^* represents the desired level for R&D and superscript m^* represents the desired level for marketing: $\sigma_{cf}^{R^*} = b_{cf}^{R^*} / (b_{cf}^{R^*} + b_{cf}^{m^*})$. The indicated budget is equal

to the current budget, adjusted with the marginal benefit: $b_{cf}^{R*} = (1 + mb_{cf}^{R'})b_{cf}^{R}$, with marginal benefit effect $mb_{cf}^{R'} = \varrho(ds_{cf}/db_{cf}^{R})/mb_{ref}$ and ϱ the investment responsiveness. If perceived marginal benefit pressures of each related budget are identical (in this case, $mb_{cf}^{R'}$ and $mb_{cf}^{m'}$), shares among these allocations remain as they are. Finally, marginal benefits take factors that are out of their control as constant. For example, producers do not control factors related to Systems & Institutions and therefore assume these as given. However, as Systems & Institutions develop, they do observe these altered factors, which they then come to take as given. This structure represents realistically the aggregate of a cluster of firms intending to act rationally with a goal to increase profits, using historical sales as a reference.

Firms reinvest a fixed share of profits. Thus, the firm budget is a sum over product margin μ_{cf} multiplied by category sales in each area $b_f = \sum_{cd} \mu_{cf} s_{cf}$. As this model is primarily concerned with dynamics of food selection across SES populations and the trade-offs firms make to target them, the potential for different strategies regarding profit margins across categories or firms are left out of scope.

Propensity to Consider (PtC_{cfp}) adjusts upwards with pressure from exposure ε_{cfp} but is also subject to decay, at consideration decay time τ^{e*}. To formulate this, we follow[130]:

$$\frac{dPtC_{cfp}}{dt} = \varepsilon_{cfp} - \frac{PtC_{cfp}}{\tau^{e*}}. \quad (5)$$

Exposure pressure ε_{fcpi} consolidates influences from different information channels i; thus, $\varepsilon_{fcp} = \sum_i \varepsilon_{fcpi}$, with channels including firm marketing and social exposure, so $i \in \{m, s\}$). Exposure pressure increases with exposure under returns-to-scale depending on the channel η_i, attaining reference value e_i, when pressure equals 1. Furthermore, social exposure pressure is, to a degree, category- rather than brand-specific ($w^{sc} \in [0,1]$), and social influence can be to a degree across rather than within population segments ($w^{sx} \in [0,1]$). Marketing exposure is brand-specific, aside from interventions inducing category-level exposure. Exposure from marketing is a function of investments, while social exposure is a function of the current consumption shares.

Finally, exposure decay time τ^{e*} is variable, decreasing in consideration[130]. A simple formulation bound s it between the minimum $\tau^{e,\,min}$ (when consideration is full) and the maximum, relative $r^{e,\,max} \geq 1$: $\tau^{e*} = \tau^{e,\,min}(1 + (1 - PtC_{cfp})(r^{e,\,max} - 1))$.

Actors respond to the value of perceived systems and institutions I_{cp}^{P}. lagging the actual infrastructure. This implies a delay structure, with the Time to Perceive Systems and Institutions Change τ^i.

$$\frac{dI_{cp}^{P}}{dt} = \frac{I_{cp}^{C} - I_{cp}^{P}}{\tau^i}. \quad (6)$$

Systems & Institutions capacity I_{cp}^{C} adjusts through a third-order delay structure[14] to the desired infrastructure capacity I_{cp}^{C*} with initial value equal to the initial value of normalized portions consumed daily S_{cp}^{N}, $I_{cp}^{C} = DELAY3I(I_{cp}^{C*}, \tau^{P}, S_{cp}^{N})$. The desired systems & institutions capacity I_{cp}^{C*} is determined through the product of perceived pressure on infrastructure and existing systems and institutions capacity $I_{cp}^{C}, I_{cp}^{C*} = I_{cp}^{P} * I_{cp}^{C}$. Perceived pressure on systems and institutions I_{cp}^{P} increases as utilization of the infrastructure increases. This effect is scaled by exponent α^{ip} [0,1]. A greater scaling effect implies that organizations responsible for capacity are more conservative to expand or contract capacity:

$$I_{cp}^{P} = I_{cp}^{CU\,\alpha^{ip}}. \quad (7)$$

Capacity utilization I_{cp}^{CU} is determined by normalized portions consumed daily S_{cp}^{N} divided by infrastructure capacity: $I_{cp}^{CU} = S_{cp}^{N}/I_{cp}^{C}$.

Finally, normalized portions consumed daily S_{cp}^{N} [0,1] equals the actual portions consumed daily S_{cp} normalized to a [0, 1] scale, achieved by dividing by maximum portions consumed daily S_{cp}^{MAX} for each food category c in each demographic segment p, $S_{cp}^{N} = S_{cp}/S_{cp}^{MAX}$.

Simulations

To create a simulated baseline, we first operationalized basic parameters setting them to heuristically plausible or neutral values (SI Tables S2–S5). Next, we operationalized the stylized baseline, the North American (Quebec) context, in terms of population, food consumption, food producer gross profits, and R&D and marketing investments, by socioeconomic status (Stage 4 above, and Table 1 and SI Tables S6 and S7). Because in the baseline scenario no specific interventions are made, businesses should continuously reinvest based on expected future profits (and identical for the two firm types). The status-quo market forces should then dictate the equilibrium market structures and consumption and investment patterns. Furthermore, as computing the steady state is prohibitive for this model, we used the following equilibrium approach to set the baseline:

1. Set parameters based on stylized characterizations assumptions (per above).
2. Use first principles to derive local equilibrium conditions for stocks where possible.
3. Run the model and observe it until it reaches equilibrium.
4. Compare with indicated baseline equilibrium settings of Fig. 1. bottom-right. If needed, adjust baseline parameters, within the ranges of Fig. 1 (right) indicated.
5. Iterate steps 3-4 until appropriate equilibrium is reached. After that, update non-equilibrium initial stock value to equilibrium value.

SI Tables S6 and S7 show the resulting quantitative parameter values and baseline settings, and the resulting baseline equilibrium values for the state variables, as qualitatively characterized in Table 1.

Finally, we operationalized the intervention scenarios using assumptions explained in SI Table S8 (column 3 "operationalization"), which we simulated and compared to the non-intervention baseline.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The results from this paper follow from a simulation-based computational analysis (all code is available, see Code Availability, below). For parameter and initialization settings of the model the paper does not make use of any primary or secondary individual-level data. All model assumptions are based on our qualitative characterizations of behavioral patterns at aggregate population-segment levels. These characterizations derive from findings across published research combined with postal-code-level data, also described in prior published peer-reviewed literature and are described in the paper (Methods). The resulting characterizations and their operationalization into model settings are visible (see SI S.3 and model) and available for inspection for each scenario and can be altered using the available model (See Code Availability).

Code availability

The workable code and other materials including variable settings and scenarios used for the analysis are available through Figshare: https://doi.org/10.6084/m9.figshare.28430903. For instructions, see SI S.8.

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J.S. designed and performed research, performed literature review and analysis, designed the computational model, performed simulation analysis, and wrote the paper. D.C. performed literature review,

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Competing interests

The authors declare no competing interests.

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