The overlooked importance of food disadoption for the environmental sustainability of new foods

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Abstract

With human food production a major driver of global environmental change, there is increasing recognition of the importance of shifting towards more sustainable dietary patterns. With wholesale dietary change notoriously difficult to implement at scale, various new food analogues have emerged to serve as qualitatively similar (e.g. taste, texture) but lower environmental impact alternatives for existing foods, particularly animal protein. While new foods may have low environmental impacts, very little is known about how reliably new products drive the disadoption (permanently reduced or ceased consumption) of existing foods. Using simple models of the interplay between adoption levels, substitution ratios of new and existing foods, and different products targeted for replacement, we explore the role of food disadoption on the global warming potential of protein consumption by a theoretical human population. We show how counterintuitive changes to the total environmental impacts attributable to food consumption are plausible following widespread uptake of ‘sustainable’ new foods if they do not reliably drive the disadoption of existing high-impact alternatives. Greater empirical evidence of how effectively new foods drive the disadoption of their intended targets is needed to prevent mass development of alternatives that exacerbate the environmental impact of human diets.

1. Introduction

Food production is a major global driver of environmental degradation and energy use, and some foods are inescapably more resource-intensive than others, even under best production practices [1–5]. Shifts towards less environmentally impactful diets are necessary to reduce the ecological burden of human food production [6, 7]. Such shifts would ideally encourage diets low in red meat, dairy, and processed foods; rich in fruits, vegetables, nuts; and moderate in vegetable oils, fish or poultry products which are well-optimised for human and planetary health [5, 7]. Yet human diets are notoriously difficult to change, as food choice is motivated by a complex web of drivers, such as price, environmental, and health effects; emotional or habitual attachment; social norms; and marketing/communication [8, 9]. Because consumers can rarely be persuaded to make sweeping changes across their dietary profile [10], replacing specific products with less impactful analogues is gaining traction as one possible strategy to reduce the cumulative environmental burden of diets [11–13].

Numerous private companies are developing or have already developed convincingly-similar
and/or lower impact alternatives to the most environmentally-costly foods to help circumvent the behavioural inertia surrounding diets. These products range from underutilized or sustainably harvested and farmed fish species, to plant-based burgers and milks, mycoprotein-based (fungal) ‘meats’, cultured cell-based animal foods, and insects and microalgae as a form of protein [11, 12, 14, 15]. Aspirations for these products to reduce the environmental impacts embedded in food consumption follow the logic that by providing consumers with low-impact alternatives that fulfill important aspects of taste and convenience [16], more environmentally-responsible food choices can ensue [12]. However, for new food introductions to reduce the total environmental impacts embedded in consumption, new products must cause the disadoption (here defined as permanently reduced or ceased consumption) of existing high impact foods in the diet.

Research on sustainable transitions and product adoption illustrate how new products can gain traction in mainstream markets, compete with existing products, and drive shifts in existing regimes [17–20]. But the extent of disadoption of existing products is often unclear in the context of new foods due to factors such as the small scale of current markets, uncertainty over which existing foods are replaced by new products, the role of influential supply-chain actors, and in sum whether these factors facilitate meaningful reductions in the environmental impacts of human diets as a whole [21]. Here we conduct an exploration of how different market adoption rates of new foods, substitution ratios with existing foods, the products used as substitutes, or the products targeted for replacement influence the embedded environmental impacts of a population’s food consumption. In particular, we ask how the extent of disadoption of existing foods influences the environmental impacts embedded in consumption as new foods deemed more environmentally sustainable are introduced. In doing so, we aim to provide a foundation for a presently nascent body of research on food disadoption and stimulate discussion around how to most effectively improve the sustainability of human diets through both technological and policy approaches.

2. Methods

We explore how new foods can affect the environmental impacts embedded in human diets through hypothetical examples which focus on protein consumption in a theoretical population. We focus on protein consumption because reducing consumption of animal-source foods high in protein is a well-recognised step in reducing the resource-intensiveness of human diets [1, 3, 7, 22]. However, these concepts are broadly applicable to the introductions of any food alternatives, as well as products outside of the diet. There are several key terms central to concepts described herein and we provide a glossary in table 1.

2.1. Data sources

The environmental sustainability of new and existing foods is most commonly compared using processed-based attributional life cycle assessment (LCA). We compare the environmental sustainability of new foods through their life cycle (cradle-to-gate) greenhouse gas (GHG) emissions per unit of protein. The environmental sustainability of foods can be characterised using numerous indicators of environmental impact including eutrophication or acidification potential, land-use, or biodiversity loss among others. But GHG emissions standardised in terms of CO₂ equivalents (i.e. their global warming potential over 100 years, GWP<sub>100</sub>) is one of the most well documented and standardised impact indicators (herein ‘impacts’) across food types [24], providing good data coverage across different foods. Focusing on a single impact also allows us to demonstrate patterns

| Term                          | Description                                                                                                                                                                                                 | Source                   |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| Adoption                      | Consumer uptake of a new product, innovation or idea—here a new food. Adoption is assumed to follow a well-established diffusion process across a population. Here we consider this adoption process to apply to the quantity of food consumed—as more consumers regularly consume a new food, the per capita consumption rate follows the same sigmoid adoption pattern. | [19]                     |
| Substitution                  | The adoption of an alternative product (the substitute) in place of an existing product that was initially desired. Substitution ratios describe the relative increase in the introduced new food for every unit decrease in the existing food. | [9]                      |
| Disadoption                   | The permanently reduced or ceased per capita consumption of a product. Broader definitions more strictly define disadoption as complete cessation of consumption, but we suggest this is an unrealistic scenario for most foods at a population level. | [23]                     |
| Environmental potential       | Defined here as the difference between the per unit environmental impacts of two foods.                                                                                                                                 | This study               |
of change that highlight plausible trade-offs from the variables of interest (see below) rather than trade-offs among impact types which is not our focus.

For the global warming potential of protein production across various products, we use mean values taken from Parodi et al [12] as these represent standardised values for a given unit (50 g) of protein production. Mean values for all protein sources are summarised in Table 2. All protein sources from Table 2 are displayed in our results to illustrate the concepts of environmental potential and used for global warming potential calculations represented in all examples. While we acknowledge this is a limited dataset around which there would be considerable uncertainty, the purpose of using these values is to illustrate patterns of change in global warming potential of consumed protein rather than quantify absolute or likely values. All values published in Parodi et al [12] account for emissions attributed to food production processes from ‘cradle to farm gate’, with system boundaries harmonised by the original study.

2.2 Exploring the role of new food introduction on the global warming potential of protein consumption

We illustrate the influence of new foods on the global warming potential of protein consumption for a theoretical population using a number of hypothetical examples. These examples incrementally explore the role of different variables in determining the relative change in total global warming potential that could eventuate when new foods are introduced. The variables of interest include:

- the differences in the environmental potential of new foods relative to existing products
- the substitution ratios between new foods and existing products targeted for replacement
- the extent of new food adoption.

We use a number of products described in Table 2 to represent ‘new’ foods in our examples. These reflect either novel foods that have been or are being developed to specifically target replacement of animal-source foods (e.g. mycoprotein or cultured meat), future foods that may emerge as alternatives to current protein sources (e.g. insect or microalgal products), or existing foods such as farmed fish (e.g. tilapia) that represent a recent but rapidly growing source of animal protein. The latter is particularly relevant as aquaculture becomes the dominant source of aquatic food globally [25] and recommendations for displacing meat with fish and seafood grow [5, 26]. For each example, we replace the existing protein with each new food individually and do not assume a mix of new foods. While the latter may be more realistic, we aimed to isolate one change among the variables of interest (e.g. adoption extent, substitution ratio, the new or existing food used) at a time to understand the implications of that change.

We use beef as our main reference for an existing protein source targeted for replacement across most scenarios as it is regularly cited as one of the most environmentally-intensive foods and an important product to reduce consumption of for less environmentally impactful diets [3, 4, 7]. We also contrast examples of new foods substituting for beef with new foods substituting for more carbon-efficient protein such as chicken or wild-caught fish (e.g. tuna). This allows us to understand the role of smaller environmental potentials in mediating changes in environmental impacts but also reflects scenarios of where introduced products have low specificity in which products they substitute for (i.e. new foods intended to reduce beef consumption may also compete with chicken or fish).

2.3 Calculating global warming potential curves

We illustrate consumer adoption of new protein sources through sigmoid adoption curves to reflect the well-documented phenomenon of product diffusion among consumers [19]. The rate of diffusion is typically mediated by product characteristics (e.g. relative advantage to alternatives or compatibility) as well as internal and external factors influencing consumer populations (e.g. people’s innovativeness, communication networks, marketing exposure). Together these factors typically drive sigmoid adoption patterns due to the differences in more rapid uptake among innovators and the early majority of consumers, slowing as a late majority and ‘laggard’ groups of consumers finally adopt in response to alleviation of concerns or out of necessity [19].

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| Product                  | GWP<sub>100</sub> (kg CO<sub>2</sub> eq. 50 g protein<sup>−1</sup>) | GWP<sub>100</sub> (kg CO<sub>2</sub> eq. kg protein<sup>−1</sup>) |
|-------------------------|-------------------------------------------------|--------------------------------------------------|
| Pulses (Phaseolus vulgaris) | 0.2                                             | 4                                                |
| Tuna (Thunnus albacares)  | 0.6                                             | 12                                               |
| Black Soldier Fly (Hermetia illucens) | 0.8                                             | 16                                               |
| Mycoprotein (Pusarium venenatum) | 1.1                                             | 22                                               |
| Cultured Meat            | 1.5                                             | 30                                               |
| Chicken                  | 2.7                                             | 54                                               |
| Tilapia (Oreochronis spp.) | 3.2                                             | 64                                               |
| Microalgae (Chlorella vulgaris) | 6.4                                             | 128                                              |
| Beef                     | 12.0                                            | 240                                              |
We constructed sigmoid adoption curves using the logistic function:

\[ y_a = \frac{c_a}{1 + e^{-x}}. \]  

(1)

\( y_a \) = a vector of per capita consumption rates (kg capita\(^{-1}\) yr\(^{-1}\)) of adopted food \( a \), \( c_a \) = the sigmoid asymptote representing the maximum consumption (kg capita\(^{-1}\) yr\(^{-1}\)) of adopted food \( a \) at time \( x_0 \), \( x \) = the domain of \([-5\,5\,i.e. [-5,5], \) relabelled so that \(-5\) equals time \( t \), and 5 represents time \( t_s \). Absolute values for \( x \) are unimportant in this context as a single increment in the \( x \) domain represents any chosen unit of time. We model disadoption curves through inverse sigmoid curves to reflect a range of basic substitution relationships between the introduction of new foods and change in use of existing products. Disadoption of the substituted product \( (y_d) \) was therefore represented by:

\[ y_d = c_d - (y_a \times s_{d,a}) \]  

(2)

where \( y_d \) = a vector of per capita consumption rates (kg capita\(^{-1}\) yr\(^{-1}\)) of disadopted food \( d \), \( c_d \) = baseline annual consumption rate (kg capita\(^{-1}\) yr\(^{-1}\)) of food \( d \) at time \( t \), and \( s_{d,a} \) = the ratio of substitution of food \( d \) by adopted food \( a \) expressed as a proportion (i.e. 25% = 0.25).

To calculate the global warming potential curves for the population’s protein consumption through time, we multiplied the per capita consumption vectors calculated above for each product by the per unit GWP\(_{100}\) of that product (table 2). These weighted impacts were then summed at each time step to yield the total global warming potential of protein consumed by the theoretical population:

\[ \text{GWP}_{\text{tot}} = \Sigma (\text{GWP}_a \times y_a) + (\text{GWP}_d \times y_d) \]  

(3)

where \( \text{GWP}_{\text{tot}} \) = a vector of the GWP\(_{100}\) of total protein consumed through time, \( \text{GWP}_a \) = GWP\(_{100}\) of adopted food \( a \) per kg of protein, \( \text{GWP}_d \) = GWP\(_{100}\) of adopted food \( d \) per kg of protein. For example, where an adopted new food \( a \) (GWP\(_a\) = 6 kg CO\(_2\) eq. kg protein\(^{-1}\)) perfectly substitutes for food \( d \) (GWP\(_d\) = 12 kg CO\(_2\) eq. kg protein\(^{-1}\)) consumed at a baseline rate of 10 kg protein capita\(^{-1}\) yr\(^{-1}\) (see below), full disadoption occurs and the vector of total global warming potential through time is calculated as follows:

\[ y_a = (0.1, 0.5, 2.7, 7.3, 9.5, 9.9) \]
\[ y_d = (9.9, 9.5, 7.3, 2.7, 0.5, 0.1) \]
\[ \text{GWP}_{\text{tot}} = \Sigma (6 \times y_a) + (12 \times y_d) \]
\[ = (119.4, 117.0, 103.8, 76.2, 63.0, 60.6). \]

Note the asymptote of the adoption (10 kg capita\(^{-1}\) yr\(^{-1}\)) or disadoption curves (0 kg capita\(^{-1}\) yr\(^{-1}\)) is approached as time tends to infinity. The change in global warming potential from time \( t \) onwards is then calculated as the difference between each element of GWP\(_{\text{tot}}\) and the first element of GWP\(_{\text{tot}}\):

\[ \Delta \text{GWP}_{\text{tot}} = (0.00, -2.4, -15.6, -43.2, -56.4, -58.8). \]

We use consumption rates of 10 kg protein capita\(^{-1}\) yr\(^{-1}\) for beef, chicken or wild-caught fish (which we exemplify through tuna), as a baseline at time \( t \). This is approximately equivalent to 20 kg of beef and chicken consumption and 13 kg of tuna consumption assuming published mean values for dry matter protein content (50% for beef and chicken and 75% for tuna [12]). These values broadly reflect conservative consumption rates from high-income countries (e.g. 23 kg capita\(^{-1}\) yr\(^{-1}\) of beef and chicken in France, and 14 and 13 kg capita\(^{-1}\) yr\(^{-1}\) of fish and seafood consumption in Austria and Germany respectively, in 2017) [27].

3. Results and discussion

3.1. The environmental potential of new foods

The difference between the environmental impacts of different foods provides a compelling argument for the savings that can be made from changes in dietary composition (figure 1). Indeed, it is in comparison with existing products’ environmental impacts that claims about the environmental sustainability of new products are often based. For example, many prospective candidates for future protein sources have a far lower global warming potential per unit of production (i.e. GWP\(_{100}\) per kcal or per protein quantity) than that of beef (figure 1). Intuitively, then, if such products can be marketed at the right price and provide a similar qualitative ‘experience’ (i.e. taste, texture) for the consumer, the reduction in GHG emissions attributable to such a shift in consumption could be substantial. We call this potential per unit benefit the environmental potential.

We suggest that such environmental potential is difficult to achieve in the vast majority of cases. To illustrate why, we use a common example to explore the theorized benefits of shifts towards consumption of new protein sources for a population of consumers under simplified circumstances. As a starting point, we consider a population that arbitrarily consumes 10 kg of protein from beef per person per year; approximating a modest consumption rate for high income countries (see methods). For illustrative purposes in our examples, we compare foods only by their global warming potential and on a per unit (50 g) protein basis (figure 1). While consumers are more likely to make food choices based on servings than on nutritional units, there is pressure for competing foods to provide nutritionally similar products to their alternatives, particularly for protein in the
3.2. Barriers to meaningful disadoption of existing foods

Implicit in functional comparisons of the environmental potentials of new food products is that substitutions of existing products with new foods are made on an equivalent basis, be it protein, calories, or some other measure. Intuitively, if alternative food products (such as insects, mycoproteins, cultured meat, farmed fish, or microalgae) directly replace beef on an equivalent protein basis through time across the population (figure 2(a)), beef is completely disadopted from diets and reductions in the global warming potential attributable to protein consumption are considerable (figure 2(b)). We do not consider such clear and demarked outcomes to be a realistic expectation of new food introductions given the temporally variable factors that drive production and consumption decisions [9]. Instead, this example serves as an exploration of important considerations and simply extrapolates the benefits of fully replacing beef with new protein sources across the population.

In practice, food choices are made among a myriad of external influences such as product price, availability, taste, variety, and appearance, in combination with internal pressures from health consciousness, environmental awareness, or social and cultural norms [8, 9, 28]. Since foods are purchased and consumed on a regular and ongoing basis, the decision to replace one food with another must also be made repeatedly. Further, because consumers typically eat a large number of foods, and these foods have a strong relationship to one another in the social process of eating, the introduction of new products may lead to unintended modifications across a consumer’s diet. Together, these factors suggest that substitution of existing products with new foods will almost certainly lead to only partial disadoption of a specific target at a population level, where each unit of new food protein adopted causes less than a complete unit of protein of the target to be disadopted.

In figure 3(a), we assume population-wide adoption of proteins from mycoprotein, insects, cultured meat, farmed fish or microalgae and that a critical mass of consumers actively replace beef with these products. But we assume low substitutability between beef and the adopted new foods, here exemplified by a 25% substitution ratio (i.e. 1 unit of new protein avoids 0.25 units of beef protein). Thus, a significant adoption of the new protein source would result in only a modest disadoption of beef.
Figure 2. Implicit expectations of the role of new foods in reducing the global warming potential of protein consumption (a) Population-wide adoption of proteins from either insects, microalgae, mycoprotein, cultured meat, or farmed fish with perfect substitution for beef (b) The change in total global warming potential of a populations' protein consumption when beef protein is perfectly substituted by those from either black soldier fly (insect), Chlorella (microalgae), mycoprotein, cultured meat, or tilapia (farmed fish). The dashed horizontal grey line at 0 on the y-axis represents the total emissions at time t.

Figure 3. The effect of low substitutability among new and existing foods on the changes to the global warming potential of protein consumption. (a) Population wide adoption of proteins from either insects, microalgae, mycoprotein, cultured meat, or farmed fish partially substituting for beef (25%) but also substituting for other dietary proteins such as pulses (75%), (b) The change in total global warming potential of a populations' protein consumption corresponding to the adoption and disadoption curves in (a). (c) Population wide adoption of proteins from either insects, microalgae, mycoprotein, cultured meat, or farmed fish substituting for other dietary proteins such as pulses (100%) rather than the intended target of beef. (d) The change in the total global warming potential of a population's protein consumption corresponding to the adoption and disadoption curves in (c). The dashed horizontal grey line at 0 on the y-axis represents the total global warming potential at time t.
Figure 4. The effect of reduced environmental potentials among new and existing foods on the changes to the global warming potential of protein consumption. (a) Population-wide adoption of proteins from either insects, microalgae, mycoprotein or farmed fish, with partial displacement of chicken or tuna (25%) and unintended dietary proteins such as pulses. (b) The change in total global warming potential of a populations’ protein consumption, corresponding to the adoption and disadoption curves in (a). The colour legend denotes the protein being used as a substitute (e.g. black soldier fly, Chlorella, mycoprotein, or tilapia), and the line-type legend denotes the protein being replaced (e.g. chicken or tuna). Colour and line type pairings illustrate the new foods introduced and those being replaced. For example, a dashed orange line represents the temporal change in global warming potential of consumed protein when wild-caught tuna is substituted by microalgal protein from Chlorella spp.). The dashed horizontal grey line at 0 on the y-axis represents the total emissions at time t.

Assuming that population-wide protein consumption remains constant, adoption of the new food also causes ‘unintended’ disadoption of other proteins in the dietary portfolio, which we exemplify with pulses (figure 3(a)). Partial disadoption is particularly problematic when the adopted new food is only slightly better in its environmental footprint than the product it aims to replace. For example, even with partial disadoption of beef, small reductions in beef consumption are unable to offset the increased GHG emissions attributable to microalgae or tilapia. As a result, the total global warming potential of protein consumed increases, despite consumers eating less beef (figure 3(b)).

To achieve net environmental benefits from consumption of new foods, it must be the consumers who eat the most impactful foods that switch to these new alternatives instead. Since diets are heterogeneous across a population, this may not be the case. Perverse outcomes from new food adoption are most likely if alternatives to current animal-source foods such as beef simply provide new options for vegetarian or vegan markets (or for those who do not consume certain meats for other reasons e.g. religion, sustainability), and little or no change in the consumption of high impact foods eventuates (figures 3(c) and (d)). This problem may be further exacerbated because as more and more sustainable food alternatives are produced and/or marketed, there is considerable risk of new foods competing with each other rather than existing high-impact foods.

There is little information regarding how effective new foods are at substituting for their intended targets. While beef is widely recognized as an animal product with a high carbon footprint [1–4, 6], the same case cannot be made for poultry or some fish species, such as tuna (figure 1). When we assume a case of partial disadoption of chicken or tuna from new food introductions instead of beef, since both existing products are relatively efficient in terms of the global warming potential of protein produced, the environmental potentials of the new foods are greatly reduced or entirely negated. Thus, only disadoption of chicken due to introduction of proteins from black soldier fly leads to a (very small) reduction in the global warming potential of protein consumption at the population level (figures 4(a) and (b)). All other considered combinations would increase the global warming potential of the total protein consumed (figure 4(b)).

Significant benefits from new food introductions also require widespread adoption of the new products. The reality is that the majority of consumers weigh taste, price, and familiarity far more heavily than environmental impacts or even health benefits [16]. Individual preferences for existing foods, ideals surrounding food consumption, and differences in the availability and price of current versus new products will limit market penetration to some extent [29]. Indeed, bridging the gap between uptake by niche consumers and the greater majority remains the largest hurdle for disruptive alternative products [30]. With foods, this may be particularly complex as many sustainable alternatives are produced and marketed by influential retailers who have a vested interest in ensuring the continuity of existing and profitable products. Marketing teams for producers of existing products also counter the communication of new foods with their own messaging, as occurred with the introduction of farmed fish into the seafood market [21, 31]. The capacity of corporate entities associated with certain food products to lobby and
acquire public relations or policy assistance to maintain any advantage of current alternatives [32] may further reduce the efficacy of market-based interventions. As a consequence, niche or partial market penetration is likely to be the best scenario many sustainable alternatives can hope for. If we reflect a case of niche adoption (arbitrarily reflected as 25% of initial beef consumption at a population level) and a (we suggest likely) scenario that only partial disadoption of beef is realized, the reductions in the overall global warming potential of protein consumption are negligible relative to previous examples (figures 5(a) and (b)). Thus, the scale of new food adoption will interplay with substitution patterns and be highly influential on the absolute change in environmental impacts these new foods could induce.

3.3. Towards a greater understanding of food disadoption

Key to the use of new foods to reduce the environmental impacts embedded in consumption is an empirical understanding of product disadoption. Since the adoption of new proteins, for instance, can replace a range of different items in the diet, understanding which products are disadopted is an empirical challenge. Without evidence that new foods can effectively cause the disadoption of the most impactful foods from consumption, these products could increase rather than reduce the environmental impacts embedded in human diets. Above, we illustrate how low-impact new foods can increase or decrease total environmental impacts depending on the extent of existing food disadoption, using simplified conceptualizations for one impact metric (global warming potential). However, greater empirical evidence regarding the observed disadoption of foods that results from new food introduction is urgently needed if new foods are to facilitate reductions in environmental impact. It is true that net environmental benefits from new product introductions rely not just on disadoption but on production displacement (the ability of new products to avoid or prevent the production of other goods). But in the context of consumer goods, disadoption of products is the mediating linchpin between consumers and production systems, and hence a key phenomenon that drives environmental outcomes [23].

Only through understanding the causal effect of introducing new foods on dietary composition can we reasonably conclude that new food products lead to less environmentally impactful diets. Answering such a question may involve causal inference in observational settings (such as quasi-experimental methods), randomized control trials, or survey methods such as discrete choice experiments. While research has begun in this area, it remains understudied. For example, a UK-based choice experiment showed that when presented to a sample of consumers with differing dietary patterns (representative of the UK public across meat-eaters, meat-reducers, and vegetarians), ground red meat or poultry minces were typically selected over mycoprotein substitutes even when controlling for price, brand, origin, production method, sustainability, and nutritional aspects [33]. This study did not attempt to estimate the extent of meat disadoption given the availability of the mycoprotein option. Modifications of consumer choice architecture (how substitute products are presented to consumers) in a European butcher shop actively elevated sales of meat substitutes compared to a pre-intervention survey and control shops [34], but did not estimate the reduction in meat sales. Van Loo et al [35] use survey methods to estimate the market share of plant-based, lab-grown, and conventional beef products, but only consider changes in branding, technology, and sustainability information, not new product introductions. Research needs to focus on not just how to elevate the adoption
of new foods, but to what extent these products, across a number of product forms and retail settings, can replace the most resource-intensive current alternatives.

There are also a number of other research avenues key to furthering our knowledge of disadoption. Firstly, working towards a prescribed definition of what constitutes disadoption in the contexts of repeated purchasing decisions, such as food consumption will be critical. Diets are constantly in flux and thus defining a static measure of dietary change is challenging [36]. Here we propose a definition of disadoption in the context of repeated purchasing decisions as the permanently reduced or ceased use or consumption of something. Second, the effects of a new food introduction are likely heterogeneous across individuals and across populations, leading to opportunities to understand the consequences of novel food introductions at different spatial scales. Third, since the environmental benefits of novel food introductions relies on production displacement, more work is needed to better understand how changes in consumer behaviour manifest as changes in production. Even if demand for the most environmentally-damaging food decreases in favour of more sustainable options, numerous actions and adaptations by different actors along supply chains may prevent production changes from being realised [14, 21]. It is worth noting that production displacement by new foods has not been widely demonstrated in other aspects of the food system to date. Despite promises of being a solution to overfishing, the rapid growth of aquaculture has largely supplemented wild fisheries and allowed market expansion of seafood rather than reducing consumption or production of wild caught fish [37–39]. This illustrates the magnitude of the challenge for some emerging products that are less similar to existing foods than farmed fish are to their wild analogues.

Sustainable transitions research suggests that innovative new foods could upscale and lead to new ways of consuming and producing food, such that these products become the ‘new normal’ [13, 17, 18]. But far greater focus has been paid to the factors catalysing new food uptake [13, 20] than to what extent these foods can selectively substitute for the most impactful products during this transition process. The use of new foods to replace existing products and improve the sustainability of human diets partly reflects a pervasive human characteristic—a tendency to search for additive rather than subtractive approaches to problem solving [40]. The appeal of new foods as disruptive interventions may also reflect the desire to circumvent a lack of political will or cohesion that, in most cases, remains incompatible with the degree and urgency of change required to production practices [7]. Nonetheless, the speed at which new foods can facilitate sustainable transitions in food systems remains unknown. Beyond product readiness, their success fundamentally depends on social acceptance, and shared mindsets, visions of change, and trust among stakeholders and policymakers to initiate change [13, 20]. How to safeguard against undesired outcomes from disruptive technologies such as those we describe here, remain poorly understood [13]. Further, while we frame the need to understand disadoption in the context of food introductions, disadoption is critical in our understanding of sustainable consumption across product categories, such as apparel, consumer electronics, and home goods, among others.

3.4. Limitations and further considerations

The examples we detail here are clearly simplified illustrations of the consequences of new food introductions. Rather than the limited modifications we describe, the introduction of a new food may cause multiple changes across dietary patterns (and plausibly outside the diet too), with implications for a range of environmental impacts beyond GHG emissions, such as water use, land use, and eutrophication and acidification potential, all of which must be considered for a robust understanding of the net environmental consequences of the new product introduction [24]. Moreover, LCA comparisons are in themselves limited due to their focus on average values that overlook important considerations of marginal changes in environmental impacts as a result of dietary change. That is, there is an assumption that the life-cycle impacts of increased production of a given food will represent current average impact values, rather than accounting for non-linear production-impact relationships [41].

The units of consumption used for comparing environmental impact can also have an important influence on sustainability assessments. While we found little qualitative difference between using GWP100 values for nutrient (protein) content or a total edible dry matter for analysing global warming changes in our examples (figure S1 (available online at stacks.iop.org/ERL/16/104022/mmedia)), foods rich in a particular nutrient can perform well using nutrient-impact comparisons among foods but poorly using total food quantities (see Tilapia in the supplementary sensitivity analysis). Given the many metrics of comparison possible across environmental, economic, and social indices, there is a clear need for context-dependent sustainability assessments that align with regional priorities (e.g. water scarcity, micro-nutrient deficiency).

We model scenarios where the introduction of new foods leads to the unintentional disadoption of pulses in addition to, or in place of, a targeted animal-source food such as beef. However, it is that likely that other foods including animal products are also unintentionally disadopted, and which have larger environmental impacts than the introduced new food, so the reductions in total environmental impact would
be greater than those we detail here. Nonetheless, reflecting the disadoption of relatively sustainable protein sources like pulses provides an important contrast to expectations and an outcome that remains plausible if sustainable new proteins largely serve vegetarian markets. Beyond environmental impacts, the social and economic consequences of shifts in dietary patterns such as changes to the nutritional composition of food consumed, the equity of food access for consumers or the distribution of economic benefits for producers must also inform assessments of the wider sustainability of new foods into the future.

As human diets at a global level incorporate more meat, fish, and dairy products [3–5, 42], it is possible that environmental benefits from new foods may be realized relative to a future state had they not been introduced. Still, these benefits depend, in part, on widespread access and adoption by those who would otherwise be eating more animal-source foods (particularly in rapidly developing economies where consumers are more price-sensitive than in high-income settings) [13], and that these products are efficient substitutes for only the most impactful foods, rather than current products that are of equivalent or superior resource efficiency. Since new foods are often introduced in specific markets with particular tastes, additional research is needed to understand how such interventions may be scaled up to make a substantial difference in the global food system. New protein sources may be particularly important in the future as demand for food strains the biophysical limits of land available for livestock production, for instance [43]. But new products that allow us to simply pivot to another form of food production (with their own associated impacts) once the biophysical limits of another are met, is not a compelling case for their effectiveness in reducing the total environmental burden of human food. Finally, and importantly, even if market-driven interventions from new foods were to successfully reduce production of the most impactful existing products, questions of how to ensure that people most dependent on food systems for livelihoods are not left behind, must be addressed. In all, these concerns question the ability of new foods to play a pivotal role in improving food and nutrition security while keeping our global food production system within ecological limits.

4. Conclusions

The permanently reduced or ceased consumption (that is, disadoption) of existing foods is key to the realization of environmental benefits from new food alternatives. While disadoption is often an implicit part of the conversation about ‘sustainable’ new foods (since the proposed sustainability is often in reference to a highly impactful target product), assuming which products are disadopted (and to what extent they are disadopted) overlooks the critical role that disadoption plays in mediating the environmental impacts of new food introductions. We illustrate how different disadoption scenarios associated with the introduction of new protein sources may manifest with vastly different environmental outcomes, and the potential for net increases in the environmental impact embedded in consumption, even when new foods are relatively low-impact. Indeed, the environmental benefits often expected of new foods may not be realized due to the interplay among consumer adoption, the extent of disadoption across the consumption bundle, and the relative environmental impacts of new and existing foods. We require a far deeper understanding of how effective new foods are at causing the disadoption of existing, resource-intensive products, otherwise we run the risk of increasing the environmental burden of human diets.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/cottrellr/disadoption.

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Author contributions

R S C and J M developed and led article design and writing of manuscript. R S C led analysis and creation of figures. B S H, H E F, and J M developed the initial concept and relevant theory. B S H and H E F secured funding. D M F contributed to methodological and code development. D M F, G D B, R G, H E F, and B S H all contributed to conceptual refinement, and manuscript development and edits.

Conflict of interest

H E F is part of the Technical Advisory Group for the Aquaculture Stewardship Council
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