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Towards a circular nutrient economy. A novel way to analyze the circularity of nutrient flows in food systems

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ABSTRACT

Recent years have seen a steep rise in the interest in nutrient circularity. In the context of food systems and waste management, nutrient circularity seems to generally encompass the reduction of nutrient losses and increased recovery of nutrients from various organic residual streams for reuse in agricultural production. Many studies that aim to contribute to improving nutrient circularity in food systems have limited the analysis to a given geographical area. But nutrient circularity likely looks different when the analysis includes what happens outside the borders of the considered area. This paper presents and discusses an analytical framework that allows for the analysis of nutrient circularity not only inside a given geographical area being considered, but also in those parts of the global food system with which the local food system interacts in terms of feed and food trade. This framework explicitly characterizes the impact of system openness associated with feed and food trade. This enables: (i) a separate discussion of four possible interpretations of nutrient circularity – internal and external input and output circularity; and (ii) an analysis of how these four circularity indicators relate to one another depending on system openness. The proposed analysis can thus reveal the extent to which a high level of nutrient circularity in the considered area comes at the cost of a decreased level of nutrient circularity in the places with which feed and food are traded, or vice versa.

1. Introduction

To improve global nutrient security, and to mitigate nutrient pollution in water bodies, societies around the world have to learn how to better recover nutrients from organic residuals – such as crop and food residues and animal and human manures – for reuse in agricultural production. It is in this light that recent years have seen a steep rise in the interest in “nutrient circularity”, “closing the nutrient loop”, “circular nutrient solutions”, and “circular nutrient economy” (Barquet et al., 2020; Cobo et al., 2019; Koppelmäki et al., 2021; Nesme and Withers, 2016; Robles et al., 2020; Rosemarin et al., 2020; van der Wiel et al., 2019; Zhao et al., 2020).

When analyzing nutrient circularity, it is essential to consider how agricultural production, consumption, and organic residual management patterns and practices interact across different relevant units of analysis: the farm (production), households and industries (consumption), the international market (trade), and public or private utilities (organic residual management). It has been hypothesized that this integration should be carried out at the “local”, “territorial”, or “bioregional” scale – a scale chosen to include similar local ecological and social characteristics where different actors can meaningfully engage with one another (van der Wiel et al., 2019). This scale has also been suggested as an appropriate and meaningful level of analysis to study transitions towards more sustainable bioeconomy systems (Wohlfahrt et al., 2019) and, more specifically, food systems (Lamine et al., 2019).

It is in the broader context of a food system design project at the local scale – the Okanagan Bioregion Food System Project – that we set out to evaluate nutrient flows for different agricultural, diet, and organic residual management scenarios. The aim was to help stakeholders in the bioregion to better understand the current level of nutrient circularity, and how it could be improved.

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Most previous nutrient flow analyses that aimed to contribute to improving nutrient circularity seem to have limited the analysis to nutrient demand and supply within a given geographical area. To better understand the entanglement over nutrients flows, both inside and outside the chosen geographical area, we felt it would be meaningful to analyze patterns inside this geographical area in relation to the interactions it has with its context in terms of imports and exports of nutrients. In other words, the analysis ought to be capable of seeing how the picture changes when enlarging the scale, by including what happens outside the borders of the geographical area being considered.

Inspired by concepts such as "ghost acres" (Borgström, 1965), "hinterland" (Galloway and Murphy, 1991), "footprint" (Rees, 1992), and "telecoupling" (Hull and Liu, 2018), our ambition thus was to take the analysis beyond the quantification of nutrient flows that lie within, or cross the geographical boundaries of the bioregion. By following feed and food imports and exports upstream all the way to nutrient inputs to crop production, and downstream all the way to the management of nutrients in organic residuals, we aimed to also consider nutrient flows that lie entirely outside of the geographical boundaries of the bioregion but relate to the bioregional food system.

In this paper, the focus is on introducing a novel analytical framework that we developed to analyze nutrient circularity in the Okanagan food system. There are three main objectives. First, to give a transparent account of a number of crucial steps and choices throughout the process that led to this framework. This includes a couple of initial thoughs on nutrient circularity (section 2) and its relationship with system openness (section 3), as well as a discussion of relevant previous work (section 4). Second, to explain in depth the conceptual framework we developed (section 5) and a couple of reflections on its potential usefulness and limitations (section 6). The calculation model implemented for, and the results from the Okanagan case study are presented in a companion paper in this issue (Harder et al., 2021).

2. Background

2.1. What is meant by nutrient circularity?

While surprisingly many studies in the field do not explicitly state what is meant by nutrient circularity, in the context of food or bioeconomy systems and waste management, the notion of nutrient circularity seems to generally encompass the reduction of nutrient losses – during agricultural production, processing, distribution, and consumption – along with comprehensive recovery of nutrients from organic residuals, for reuse in agricultural production. A commonly agreed indicator for nutrient circularity in food and bioeconomy systems seems yet to remain elusive. Nutrient circularity has been defined, for example, with a focus on waste management – as the fraction of nutrients in waste streams that are recycled to agricultural production (Senthilkumar et al., 2014). This circularity indicator could be referred to as 'output circularity'. Nutrient circularity has also been defined with a focus on agricultural biomass production – as the fraction of total nutrient inputs that are supplied from waste streams (Koppelmäki et al., 2021). This circularity indicator could be referred to as 'input circularity'. In general terms, nutrient circularity indicators seem to boil down to some sort of comparison between nutrient inputs to agricultural production (in terms of fertilizer inputs only, or considering nutrient inputs more broadly) and nutrients in organic residuals (in terms of what is actually recirculated, or considering what is potentially available) (e.g. Akram et al., 2019a; Akram et al., 2019b; Leinonen et al., 2019; Metson et al., 2016b; Parchomenko and Borsky, 2018; Trimmer and Guest, 2018).

2.2. How open are nutrient flows in modern food systems?

Over the past hundred years or so, modern agriculture has become increasingly dependent on inputs of fertilizers, irrigation water, and pesticides. The goal was to improve crop yields to satisfy the growing demand for food due to an increase in population (Boserup, 1981; Hayami and Ruttan, 1985). The high external inputs of synthetic fertilizers meant that the internal recycling of nutrients in agroecosystems became more and more irrelevant in sustaining yields (Arizpe et al., 2011; Conforti and Giampietro, 1997). The breaking of nutrient cycles in agricultural production was further aggravated by the progressive globalization of the economy, which boosted international trade of agricultural commodities (Nesme et al., 2018; Nesme et al., 2016). In particular, the specialization of modern agriculture (in terms of farms or even entire regions that focus on either crop or animal production) has generated sizeable flows of animal feed across distant geographic areas (Cadillo-Benalcazar et al., 2020; Jones et al., 2013; Renner et al., 2020). Taken together, industrialization, globalization, and specialization of agriculture thus have brought about a dramatic linearization of nutrient flows across the globe (Gruber and Galloway, 2008; Smil, 2000; Vitousek et al., 1997).

2.3. Why is nutrient circularity important and how can it be achieved?

The growing divide between urban and rural populations entails an asymmetric flow of plant nutrients from the countryside to cities. This, together with the global trade of agricultural commodities, tends to lead to an accumulation of nutrients in the places where feed and food are consumed, and a depletion of nutrients in the places where feed and food are produced. Thus, the linearization of nutrient flows generates problems both on the supply and the sink side. Nutrient losses along the entire food chain – from agriculture and food processing to consumers and organic residual management – severely compromise water quality (Steffen et al. 2015). At the same time, the need to continuously produce new synthetic fertilizers to maintain agricultural productivity raises issues in terms of nutrient security (Cordell et al., 2009; Manning, 2015; Razon, 2018).

A logical solution to these problems would be to gather the organic residuals that accumulate in the places where feed and food is consumed, and send them, or the nutrients contained therein, back to the places where feed and food is produced. However easy this idea is to conceive, its implementation in practice is difficult, as it is hampered by factors such as:

(i) The economic cost of recovering and utilizing nutrients in organic residuals increases with the distance the residuals have to be hauled, or with the technical processes needed to extract and concentrate nutrients so that they can be transported more easily. This may imply competitive disadvantages compared with the use of synthetic fertilizers (Cobo et al., 2019).
(ii) The social practices associated with urban lifestyles for the moment seem to be incompatible with large scale recycling of organic residuals. For instance, modern urban residential settings may prevent an effective handling of organic residuals as a result of insufficient sorting (Ordoñez et al., 2015).
(iii) Technologies that are appropriate to achieve nutrient recirculation at scale are being researched and developed (Harder et al., 2019; Johannesdottir et al., 2020), but their implementation and upscaling in practice remain a key challenge (Andersson et al., 2016; Barquet et al., 2020).

The complexity of the problem thus necessitates the consideration of a range of factors relating to the functioning of food systems – defined as the aggregate of food production, food processing, distribution, storage, preparation, and final consumption (Malassis, 1979) – to which one has to add the trade of agricultural products and live animals, as well as the handling of organic residuals. In other words, moving towards a more circular use of nutrients will require a total rethinking how we farm, eat, and manage organic residuals (McConville et al., 2015; Sutton et al., 2013; Withers et al., 2020).

2.4. How does nutrient circularity relate to the circular economy and bioeconomy?

The concepts of "circular economy", "green economy", and "bioeconomy" (often combined together into "circular green bioeconomy") are the stars of the discussions over sustainability in Europe (EC 2015; 2018; 2020) and are becoming the pillars of a new generation of "green deal" policies that are expected to solve the sustainability crisis both in the European Union (EC, 2019) and the United States (US House Resolution 109, 2019).

In the years to come, according to the concept of bioeconomy, we should expect a substantial increase not only in the demand for food – to feed a still growing population eating richer diets – but also in crops that can be used as building materials or in "biorefineries" – to produce fuels, power, chemicals, and even commodities like clothes. When looking at these new uses of agricultural commodities, we can fully appreciate the magnitude of the sustainability challenge to be faced in terms of a "circular bioeconomy". Not only will it be necessary to eliminate the lack of nutrient circularity associated with the current use of fossil energy inputs in modern agriculture, but also will the massive increase in the demand for food, fuel, and fiber require a boost in agricultural production – which implies a major increase in the magnitude of nutrient flows to be recirculated.

Moving to a sustainable circular bioeconomy crucially depends on biological and technical processes capable of recirculating nutrients in the right mix and at the right pace (and using only renewable energy). If we are serious about a sustainable circular bioeconomy, and sustainable food systems, we have to have robust tools to study (diagnose) and explore (simulate) the factors determining the circularity of nutrient flows.

3. Nutrient circularity and system openness

We conceive of system openness as the degree to which nutrients removed from agricultural land in one place make their way into organic residuals in another place. In the absence of imports and exports – or if imports and exports were in perfect balance in terms of their nutrient content – nutrient removal from agricultural land equals nutrients available in organic residuals. The more that crop nutrient removal and nutrients in organic residuals in a given geographical area deviate from one another, the more open the system is. System openness can lead to what we refer to as nutrient accumulation and depletion – imbalances in the availability of nutrients in organic residuals that are the result of imbalances in feed and food imports and exports, as illustrated in Fig. 1.

The way we conceive of nutrient accumulation and depletion is that the origin of feed and food crops is what determines the origin of the nutrients in organic residuals. In case of animal production, this means that it is solely the origin of the feed that determines where the nutrients are deemed to come from, not the location of livestock production. In other words, nutrients in manure generated by livestock produced internally with imported feed are considered to originate outside rather than inside the considered area. In a similar vein, those nutrients in food

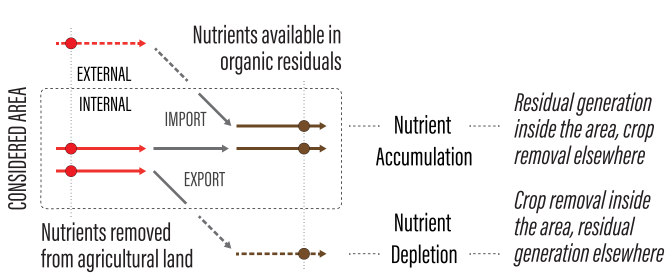

Fig. 1. The concept of nutrient accumulation and depletion. Note that nutrient accumulation and depletion are to be seen as relative to a situation where nutrient imports and exports with feed and food trade are balanced.

waste and human excreta that relate to the consumption of animal products produced internally with imported feed are also considered to have their origin outside the considered area.

We would like to emphasize that the concept of nutrient accumulation and depletion by no means intends to imply that all nutrients in organic residuals should go back to exactly the place where the feed and food crops were produced. Rather, the idea is for the concept to facilitate the quantification of how much of the nutrients in organic residuals might need to be sent across the spatial boundaries of the considered area to compensate for imports and exports of feed and food.

4. Discussion of relevant previous work

4.1. Nutrient flow analyses

Nutrient flow analyses – by providing a diagnostic analysis of past and current patterns of nutrient flows, and simulations of plausible options – can help identify drivers of unsustainable patterns, as well as, barriers and opportunities for moving towards more sustainable patterns. Nutrient flows have been studied in different areas of the world, for different geographical units from small to global scales (e.g. farm or field, city, municipality, country, region, ecosystem, watershed, globe) and for different socio-technical-ecological systems. Some analyses have focused on all sectors of society (e.g. Chowdhury et al., 2014; Jedelhauser and Binder, 2015 and studies reviewed therein), while others have focused on a specific sector like the waste sector (e.g. Rahman et al., 2019 and studies reviewed therein) or a specific flow like nutrient losses from agriculture to the aquatic environment (e.g. Ulén et al., 2007 and studies reviewed therein). Our interest here is primarily with nutrient flow analyses of agro-food-waste systems, which are increasingly carried out at the local level (e.g. van der Wiel et al., 2019 and studies reviewed therein). These can be roughly divided into two broad approaches, here referred to as *territorial* and *footprint* approach.

4.1.1. Studies following a territorial approach

The territorial approach is the more common approach found in the literature. It focuses on a specific geographical area and considers nutrient flows inside and across the spatial boundaries of this area (the internal component) while flows that are related but entirely outside its spatial boundaries (the external component) are not considered. Studies that follow a territorial approach generally focus on one or both of the following two perspectives: broadly mapping nutrient flows that enter or leave the area and between subsystems within the area; or estimating nutrient circularity by contrasting fertilizer demand by crop production with actual or potential nutrient supply from organic residuals such as animal manure, food waste, and human excreta. This is illustrated further in Fig. 2.

Within both perspectives, studies are becoming ever more refined. Those that focus on mapping flows for instance by the inclusion of carbon flows (Binder and Patzel, 2001; Le Noë et al., 2017), the investigation of long-term trajectories (Bellarby et al., 2018; Le Noë et al., 2018; Spiess, 2011), or the explicit consideration of agricultural trade at the sub-national level (Le Noë et al., 2018, 2017). Those that focus on contrasting demand and supply for instance by improved spatial resolution (Leinonen et al., 2019; Metson et al., 2016b; Parchomenko and Borsky, 2018) or calculation models (Leinonen et al., 2019), or by accounting for nutrient travel distance (Akram et al., 2019b; Trimmer and Guest, 2018), soil suitability (Trimmer et al., 2019), plant-availability (Hamilton et al., 2017), fertilization regimes (Hanserud et al., 2016), or different waste management scenarios (Wielemaker et al., 2018).

4.1.2. Studies following a footprint approach

The footprint approach is the less common approach. It usually starts from food consumption in a given geographical area, such as a country or city, and then estimates associated nutrient flows: upstream in the agro-food systems that supply food, and downstream in the solid and

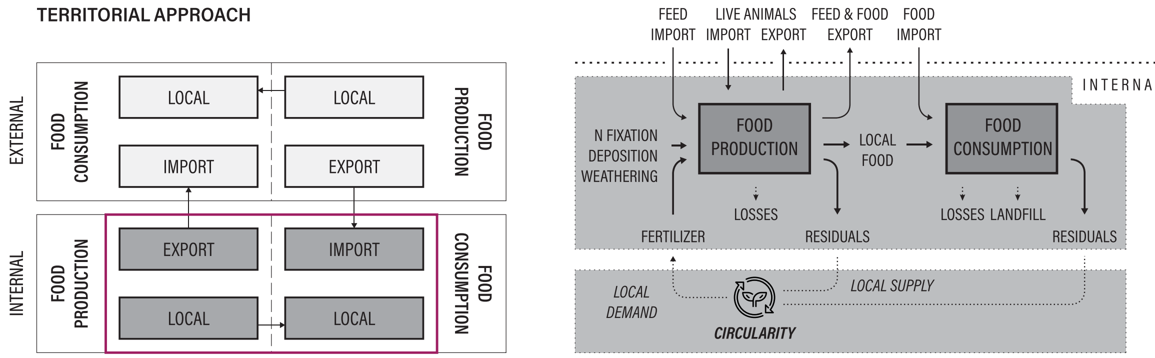

Fig. 2. 'Territorial' approach to nutrient flow analyses. This approach covers the full extent of food production and consumption in a given geographical area, including import and export flows, but does not consider flows that are outside of but related to the food system in the chosen area.

wastewater management systems that take care of organic residuals (Esculier et al., 2019; Metson et al., 2020, 2016a). This is illustrated further in Fig. 3. Studies following this approach bear resemblance to the concept of nutrient footprints (Cattell Noll et al., 2020; Grönman et al., 2016; Leach et al., 2012). The focus can be on mapping nutrient flows or on estimating nutrient circularity.

4.2. Methodological gap

Nutrient flow analyses that follow a territorial or footprint approach both have their merits. However, neither of the two approaches in isolation provides all information required to assess all nutrient flows associated with agricultural production and food consumption in a given geographical area. These nutrient flows are inevitably linked to the considered area, irrespective of whether they lie inside the area (internal component) or outside (external component). As illustrated in Fig. 4, the territorial approach misses for instance nutrient inputs required outside the considered area to grow the imported feed and food, while the footprint approach misses the nutrient inputs required in the considered area to grow the feed and food that is exported. Moreover, neither of the approaches considers for instance organic residuals generated after consumption of feed and food exported from the considered area.

A complete picture can be obtained only by combining and extending the territorial and footprint approaches, by taking as starting point the complete food system that is internal to the considered area (comprising both agricultural production and food consumption in its entirety), and then following feed and food imports and exports both upstream, all the way to nutrient inputs, and downstream, all the way to organic residual management. The type of analysis that emerges from this combination and extension of the territorial and footprint approaches is visualized in Fig. 5. To our best knowledge, no previous study has done this.

5. Towards a novel way to structure the analysis

The novel way to structure the analysis of nutrient circularity in food systems that is introduced and explained here aims to close the gaps that were previously identified.

5.1. Five subsystems

The starting point is to establish the 'grammar' of the analysis in terms of an expected set of relations over the five main subsystems commonly included in nutrient flow analyses for agro-food-waste systems: grass and crop production, livestock production, food processing, food consumption, and residual management (see also van der Wiel et al., 2019; Van Zanten et al., 2018). The subsystems and the relationships between them are illustrated in Fig. 6.

5.2. Distinction of internal and external subsystem components

Due to feed and food trade, each subsystem has not only a component inside the spatial boundaries of the considered geographical area (internal to the area), but also one outside (external to the area). Thus, for each of the five subsystems, there are two notional representations: one that observes the interactions of the internal components and one that observes the interactions with components that are external to the area being considered. This entails that the connections between individual subsystem components are rather complex, see Fig. 7.

5.3. Disentangling nutrient flows

Several of the flows in Fig. 7 have multiple components that reflect where feed and food are produced and consumed. For example, the internal flow of food commodities from processing to society can be

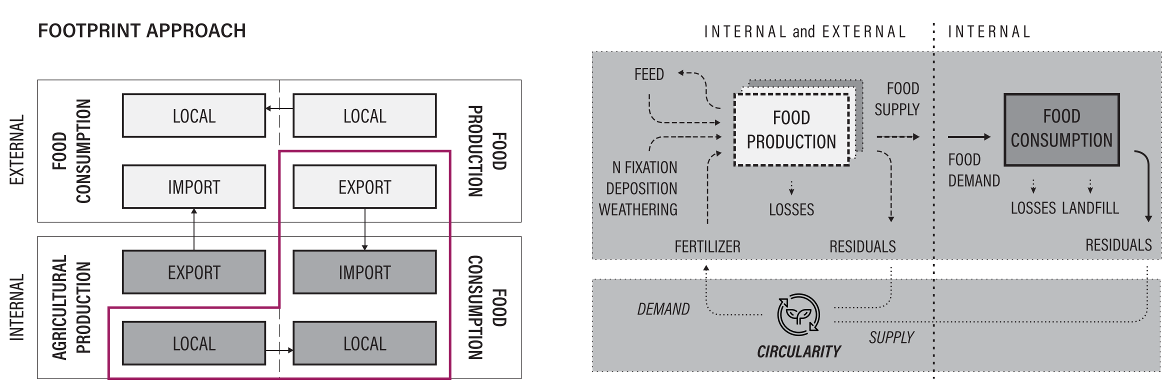

Fig. 3. 'Footprint' approach to nutrient flow analyses. This approach usually starts from food consumption in a given geographical area and includes related flows in agricultural production both inside and outside this area.

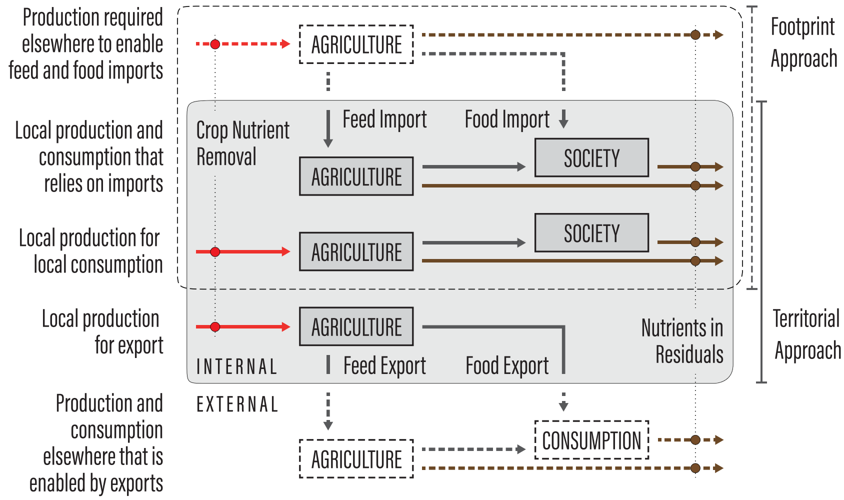

Fig. 4. Scope of the territorial and footprint approaches. Solid lines represent flows that are internal to the considered geographical area, dashed lines represent flows that are external to this area.

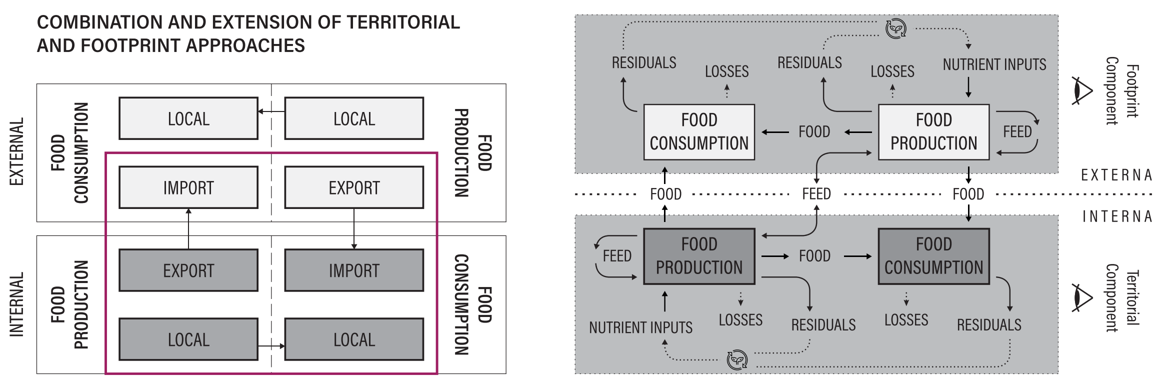

Fig. 5. Combination and extension of the territorial and footprint approaches. Both food production and consumption in a given geographical area are considered in their entirety. Both imports and exports of feed and food are followed all the way upstream to nutrient inputs and downstream to organic residual management.

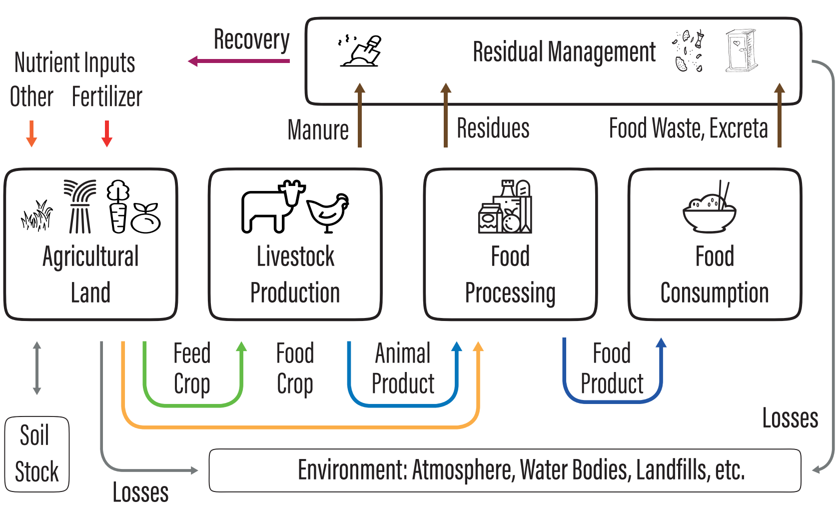

Fig. 6. Subsystems and their relationships. Note that conceptually, there are no nutrient losses during livestock production, food processing, and food consumption. Any nutrient losses other than from agricultural land take place in residual management. For example, for a cow in a livestock operation, this means that residual management starts right after manure excretion. Note that enteric nitrous oxide emissions from ruminants are negligible in comparison with emissions from manure (Parker et al., 2018).

divided into one component that comprises food commodities that originate in crops grown inside and one that comprises those that originate in crops grown outside the considered area. Likewise, the internal flow of animal products from livestock to processing can be divided into four components depending on whether feed was grown internally (inside the border of the food system under analysis) or externally (outside the borders), and animal commodities are consumed internally or externally. Of course, the distinction between internal and external subsystem components, and between individual components of nutrient flows, is less clear-cut in reality than in the conceptual representation. For example, a cow may be fed both domestic and imported feed, while milk and meat may go to both domestic consumption and

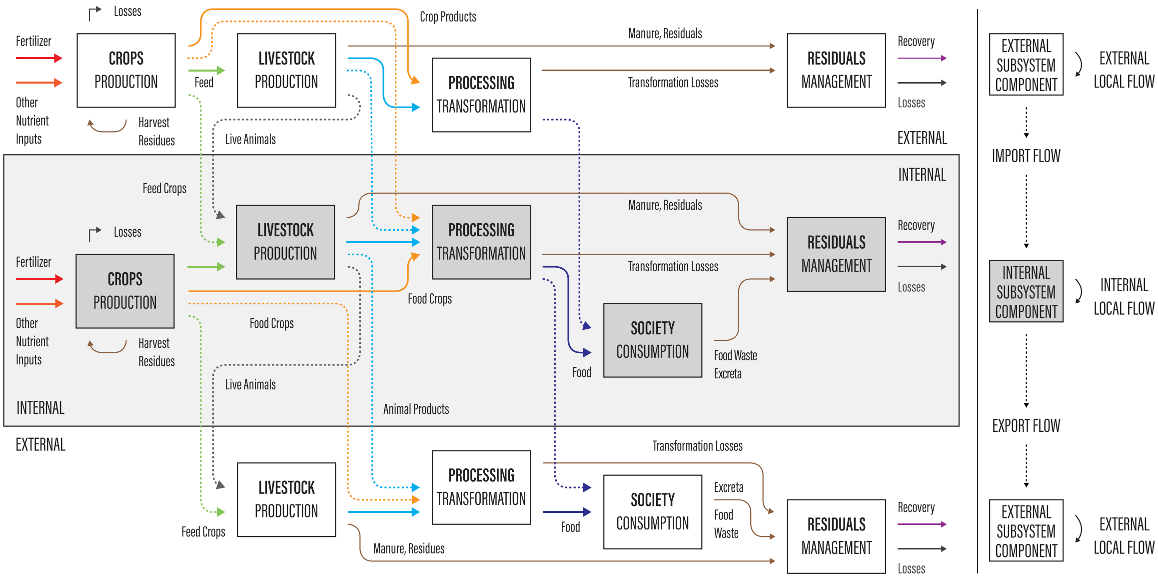

Fig. 7. Conceptual model underpinning the analysis of nutrient circularity in food systems. It consists of individual subsystem components that are internal or external to a given geographical area being considered, as well as their relationships in terms of nutrient flows. Note that, in order to improve readability, the external component has been split into two parts: one that relates to the import of feed and food to the considered area, and one that relates to its export. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

export. Likewise, because import or export can take place prior to or after food processing, some of the processing is likely to take place internally and some externally. Nevertheless, we think it is helpful to disentangle subsystems and flows into components, as this will increase conceptual clarity and allow to track nutrients from inputs to crop production to organic residuals, as a function of where feed and food are produced and consumed. To allow for a better understanding of all possible linkages between subsystem components, overall, we found it useful to distinguish four clusters, which can be further disentangled into ten individual pathways, as described in Fig. 8. They could be seen as layers of Fig. 7 if put on top of each other, pathways map onto clusters and clusters map onto the conceptual model.

5.4. Assessing nutrient circularity

As stated in the introduction, nutrient circularity in food systems seems to generally be conceived of as some sort of comparison between nutrient inputs to the food system (e.g. in terms of fertilizer inputs, or considering nutrient inputs more broadly) and nutrients in organic residuals (e.g. in terms of what is actually recirculated, or considering what is potentially available), see Fig. 9.

Fig. 9 thus distinguishes two kinds of nutrient circularity: output circularity (which focuses on outputs from the system in terms of nutrients in organic residuals); and input circularity (which foscuses on inputs to the system in terms of fertilizers or agricultural and food commodities). In addition, accounting for system openness allows for separate estimation and comparison of the internal and external component of nutrient circularity in the considered food system. In this regard, it should be noted that, because of commodity trade and differences in agricultural and organic residual management practices, internal and external input and output circularity are unlikely to be at the same level.

There is not only one way to recirculate nutrients recovered from organic residuals into the food system. Obvious and well established ways include the reuse of (nutrients recovered from) organic residuals as fertilizers in crop production or as feed in livestock production. Other ways include the use reuse of wasted food in food processing (e.g. making juice from wasted fruit), or even the direct reuse of wasted food in food consumption through for example dumpster diving (which may be seen as desirable by some and as problematic by others) (Carolsfeld and Erikson, 2013; Eikenberry and Smith, 2005; Lehtonen and Pyyhtinen, 2021; Rombach et al., 2016).

While output circularity remains unaffected by whether nutrients are recirculated to for instance crop production or livestock production, for input circularity this matters. For instance, recirculating nutrient to livestock production rather than crop production means that nutrient use efficiency in crop production no longer plays in. This can increase input circularity, for example when the animals would otherwise have been fed with grain that was fertilized and subject to significant nutrient losses from the soil. It can also decrease input circularity, for example when the animals would otherwise have been grazed on pasture that is not fertilized and acts as a “concentrator” of nutrient inputs like atmospheric deposition, symbiotic fixation, and soil weathering. For the Okanagan case study, which is presented in detail in a companion paper in this issue (Harder et al., 2021), we assumed that all nutrient recirculation takes place to crop production. For other case studies, this assumption might need to be reconsidered.

6. Discussion and outlook

With continuing nutrient pollution in water bodies and growing concern about future nutrient security, the need for recirculating nutrients from organic residuals to agricultural production is becoming ever more apparent. Nutrient management is often informed by nutrient flow analyses. Not surprisingly, method development in this field has been strong over the past years. In studies that follow a “territorial” approach, one can typically find statemens such as that a given region could supply a certain percentage of its nutrient demand with nutrients available in organic residuals. What is rarely explicitly stated, however, is that a certain fraction of the available nutrients are originating from outside the considered region – and that not sending these nutrients outside the region would reduce nutrient circularity external to the region by a certain percentage. This is where the analytical framework proposed in the present paper comes in and opens up new possibilities for innovative ways to analyze nutrient circularity in food systems.

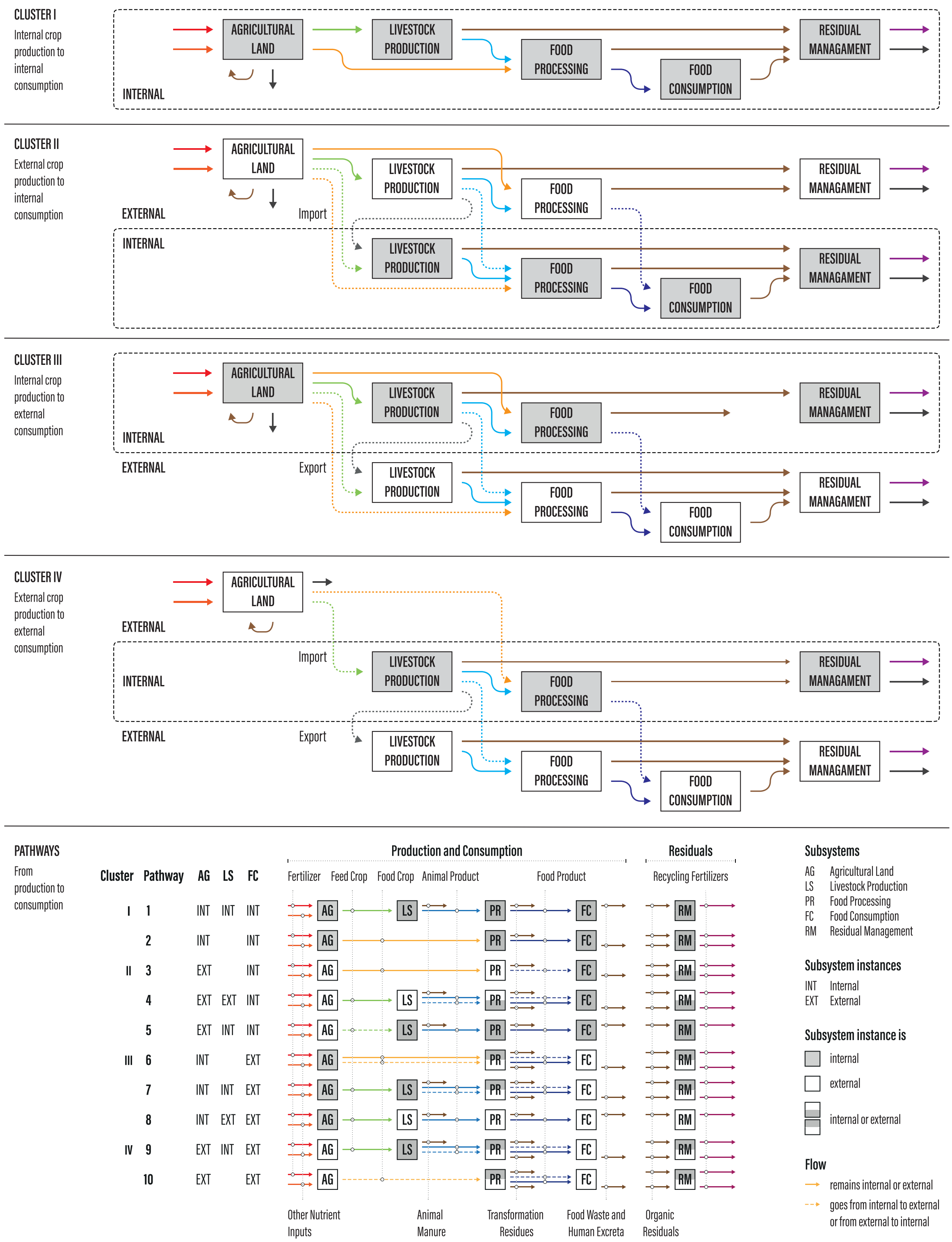

Fig. 8. Disentangling flows of nutrients into clusters and pathways.

6.1. *Usefulness of the framework*

Analyzing and understanding the entanglement over nutrients flows, both inside and outside the chosen geographical area, is important to assess whether a high internal nutrient self-reliance in the considered area is obtained at the cost of a poor external nutrient self-reliance in the places with which feed and food are traded. For in the long run, it will be important to learn how to balance nutrient flows not only within, but also between individual geographical areas, notably between areas of net commodity import and export. The (less than ideal) alternative is that areas that are net importers may think they can get away with lesser levels of nutrient recirculation, while areas that are net exporters continue to rely on large inputs of mineral fertilizers or depleting their soil nutrient stocks (Jones et al., 2013).

The proposed analytical framework explicitly breaks down individual nutrient flows into components that reflect individual pathways from crop production to livestock production to food processing and consumption – for example from feed production outside the considered

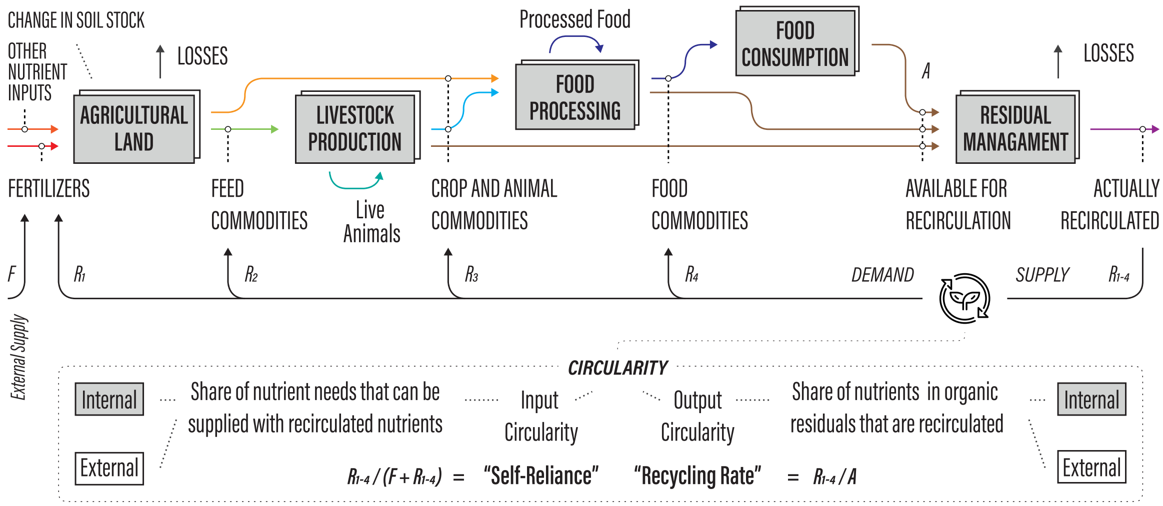

Fig. 9. More nuanced analysis of nutrient circularity, distinguishing four interpretations of nutrient circularity.

area via livestock production inside the area to food processing and consumption outside the area. This enables a separate discussion of four kinds of nutrient circularity – internal and external input and output circularity – as well as how they relate to one another and to system openness. Ideally, the analysis is performed for multiple nutrient elements (e.g., nitrogen, phosphorus, and potassium) as circularity can be expected to differ for different nutrient elements. The analysis could also be extended to include carbon.

6.2. *Limitations of the framework*

The analytical framework presented here addresses what could be described as "theoretical" levels of nutrient circularity. The feasibility in practice depends on factors such as social acceptance, economic viability, and the availability of adequate technological solutions. Addressing these aspects needs complementary analysis.

Similarly, it is important to note that comprehensive nutrient circularity is a necessary factor for sustainable circular bioeconomy systems, but not a sufficient one by itself. Once nutrients are recirculated to agricultural production, it is biological processes that recycle the nutrients from the soil (or other growth medium) back into new agricultural commodities. This means that when looking at the circularity of the bioeconomy from a biophysical point of view, one has to acknowledge that the vast majority of the energy needed for nutrient recirculation – from organic residuals all the way to new agricultural commodities – is provided by the sun and by biological processes. The characteristics of these natural processes entail the existence of strict limits on the pace and the density of the flows of nutrients that can be recycled when using renewable biological resources. These biophysical limits should be better understood to check the (limited) potentiality of technical innovations and business models in boosting the recycling of nutrients to support a circular bioeconomy at a large scale.

6.3. *Future work*

The approach presented here was developed and applied as part of a food system design project in the Okanagan bioregion, BC Canada. The calculation model implemented for, and the results from the Okanagan case study are reported in a companion paper in this issue (Harder et al., 2021). To further evaluate how this approach could best inform policies regarding diets, agriculture, and organic residual management, it would be desirable to further develop and test this type of analysis in the context of further case studies. Such case studies could study (diagnose) the current situation, or explore (simulate) different scenarios for diets, agricultural and organic residual management practices. Although developed for a bioregion, this kind of analysis should be applicable also at other spatial scales, ranging from for example a village or city to an entire country or even continent. Likewise, even though developed to analyze nutrient circularity in food systems, the conceptual framework, after some adjustments, should also be applicable to analyze the circularity of nutrient flows in bioeconomy systems more broadly.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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