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Full length article

Assessing the circularity of nutrient flows related to the food system in the Okanagan bioregion, BC Canada.

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ABSTRACT

The “circular bioeconomy” is extensively discussed in science and policy, and its implementation in practice is considered to be a panacea for fixing many current sustainability problems. The circular bioeconomy crucially depends on biological and technical processes capable of recycling nutrients in the right mix, at the right pace, and using only renewable energy. The current lack of circularity of nutrient flows is a critical factor that hampers sustainable food and bioeconomy systems. If we are serious about the sustainability of food and bioeconomy systems, we have to develop more robust tools to study (diagnose) and explore (simulate) the factors determining the circularity of nutrient flows. This paper applies a novel analytical framework to assess the circularity of nutrient flows in modern food systems. This framework can help understand the potentialities of proposed changes in relation to reducing nutrient losses and the dependence on nutrients mined from finite deposits. More specifically, in this paper, we illustrate a quantitative assessment of the flows of nitrogen, phosphorus, potassium, and magnesium in a case study – the food system of the Okanagan bioregion in BC Canada. Our study suggests that the proposed approach is effective to inform nutrient management policies in bioregional food systems. In particular, an assessment of the openness of nutrient flows flags the importance of managing organic residuals for comprehensive nutrient recovery and reuse – an activity that is still often systematically neglected due to large feed and food imports and the availability of cheap synthetic fertilizers. This type of analysis is essential if we want to develop effective policies for more sustainable management of nutrients in food and bioeconomy systems.

1. Introduction

In recent years, the concepts of “nutrient circularity”, “closing the nutrient loop”, “circular nutrient solutions”, and “circular nutrient economy” have gained traction (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). This echoes the increasing understanding that, in order to mitigate nutrient pollution in water bodies and improve global nutrient security, societies around the world have to learn how to minimize nutrient inputs in agricultural production while maximizing the recovery of nutrients from organic residuals – such as crop and food residues and animal and human manures – for reuse in agriculture.

For millennia, nutrient supply in agriculture depended on natural processes like soil weathering and biological nitrogen fixation, as well as the internal recycling of nutrients through the use of organic residuals as organic fertilizers. But with the increasing dependence of modern society and agriculture on fossil energy (Cottrell, 1955; Leach, 1976; Pimentel and Pimentel, 1996; Smil, 2000, 1991, 1988, 1987), agricultural productivity has become dependent on continued external nutrient inputs. High inputs of synthetic fertilizers in particular meant that the internal recycling of nutrients in agroecosystems has become more and more irrelevant in sustaining yields (Arizpe et al., 2011; Conforti and Giampietro, 1997). Today, global industrial agricultural production relies on high inputs of nutrients mined from finite reserves, produced using fossil fuels, and transported over large distances (Boulaine, 2006;

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Ciceri et al., 2015; Erisman et al., 2008). A significant share of these nutrient inputs are lost from agriculture and other parts of society to the atmosphere, water bodies, landfills, and so forth. This linearization of nutrient flows has been aggravated by the globalization and specialization of agriculture, as well as urbanization (Harder et al., 2020). Moreover, it has generated problems both on the supply and on the sink side: linear nutrient flows severely compromise water quality (Steffen et al., 2015), nutrient security (Cordell et al., 2009; Manning, 2015; Razon, 2018), and soil health (Jones et al., 2013).

Moving toward a more circular use of nutrients is not trivial. On the one hand, the growing divide between urban and rural populations entails an asymmetric flow of nutrients from the countryside to cities. Together with agricultural trade, this tends to lead to a concentration 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 (Cadillo-Benalcazar et al., 2020; Jones et al., 2013; Renner et al., 2020). On the other hand, there are issues related to social practices and acceptance, economic costs, and the implementation and upscaling of appropriate nutrient recirculation technologies (Barquet et al., 2020).

At the same time, moving towards a more circular use of nutrients becomes ever more important (Harder et al., 2020; Nesme and Withers, 2016; Sutton et al., 2013; Trimmer et al., 2019b, 2017). On the one hand, there is a still growing population eating richer diets. On the other hand, the increasing popularity of the concept of “circular bioeconomy” in science and policy (Hadley Kershaw et al., 2021; Yaremova et al., 2021) means that, in the years to come, we should expect an increased demand for crop biomass for use as building materials or in “biorefineries” to produce fuels, power, chemicals, and even commodities like clothes.

Achieving a sustainable circular bioeconomy crucially depends on biological and technical processes capable of recycling nutrients in the right mix, at the right pace, and using only renewable energy. If we are serious about the sustainability of bioeconomy systems, there is a need for robust tools to study (diagnose) and explore (simulate) the factors determining the circularity of nutrient flows. Even when focusing only on the circularity of nutrient flows in the food system, tracking nutrient flow across geographical scales is challenging.

When studying possible trajectories towards a more circular use of nutrients in modern food and bioeconomy systems, it is important that the analysis of nutrient flows is carried out at an appropriate scale. It has been hypothesized that the “local”, “territorial”, or “bioregional” scale – a scale chosen to include similar local ecological and social characteristics – is meaningful to restore nutrient circularity (van der Wiel et al., 2019), and to study transitions towards more sustainable food systems (Lamine et al., 2019) and biomass systems more broadly (Wohlfahrt et al., 2019). Then, to understand the entanglement over nutrients flows, both inside and outside the chosen bioregion, it would be necessary to analyze not only patterns of nutrient flows inside the bioregion but also how these patterns interact with their context, in terms of imports and exports of nutrients. This would require that the analysis is structured in such a way that it is capable to show how the picture changes when the scale of the analysis is enlarged beyond the spatial boundaries of the bioregional food or bioeconomy system being considered.

The work presented here was carried out as part of a food system design project in the Okanagan bioregion, BC Canada. The goal was to conduct an appraisal of the circularity of nutrient flows in the food system and organic residual management infrastructure. To this end, we mapped the flows of nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) that are relevant to the food system in the Okanagan bioregion. In doing so, we included all nutrient flows related to food production and consumption in the Okanagan, irrespective of whether nutrient inputs and organic residual generation are located inside or outside of the spatial boundaries of the bioregion. In other words, by following imports and exports upstream, all the way to nutrient inputs to agricultural production, and downstream, all the way to organic residual management, the analysis also considered nutrient flows that relate to food production and consumption in the bioregion but lie entirely outside its spatial boundaries. This way, it is possible to quantify the circularity of nutrient flows not only inside the bioregional food system being considered, but also how the bioregional food system impacts nutrient circularity in those parts of the global food system with which it interacts in terms of feed and food trade. Such analysis can reveal the extent to which a high nutrient circularity in the bioregion being considered comes at the cost of a reduced nutrient circularity in the places with which feed and food are traded, or vice versa. To our best knowledge, no previous study has done this. For more details on how our analytical framework differs from previous research, the reader is referred to a companion paper in this special issue (Harder et al., 2021). In the present paper, there are two main objectives: (i) to describe how we operationalized the proposed framework into a calculation model tailored to the Okanagan bioregion case study; (ii) to showcase the potentiality of this framework to quantify the circularity of nutrient flows and the implications of system openness on managing nutrients in organic residuals.

2. Methods

2.1. The Okanagan bioregion

The Okanagan Valley, also known simply as the Okanagan, is a region located in the Southern Interior of British Columbia (BC), Canada (Fig. 1a). With a population of 362,000 and a total area of just above 2 million hectares, it is one of the two most important agricultural regions in BC, and one of the largest producers of temperate zone tree fruits, wine grapes, and wines in Canada (Robert et al., 2018).

Crop production in the Okanagan takes place mainly in the center of the bioregion, on and near the valley bottoms, with food crops grown mainly close to the population centers, and feed crops and managed grassland extending progressively further away (Fig. 1c). Intensive livestock production coincides with areas of intensive feed production and is concentrated in two areas in the north of the bioregion. In the foothill areas located towards the periphery of the bioregion, grazing on rangeland and natural pastures is commonplace. Like most bioregions, the Okanagan produces feed and food for consumption in and outside the bioregion, and the feed and food consumed in the Okanagan is produced in and outside the bioregion. In the baseline year 2016, food waste mostly ended up on landfills as plans for separate collection of food waste had not been yet implemented. Municipal wastewater treatment was available for the larger and some smaller communities (Fig. 1b), amounting to an overall coverage of about 60%. The remaining 40% of the population were connected to onsite sanitation systems of some sort. More details on administrative divisions, agricultural production, residual management, and associated data sources can be found in the Supplementary Material.

The Okanagan bioregion makes for an interesting and appropriate case study for two reasons. First, its population strongly relies on imported food while agricultural production is primarily export-oriented. Second, various actors in the bioregion are actively pursuing a food system future in terms of regionalizing the food system, sustainable diet, environmental stewardship, and investing in new organic residual management infrastructure.

2.2. Analytical framework

2.2.1. Structure of the analysis

The development of the analytical framework that underpins this paper is described in detail in a companion paper in this special issue (Harder et al., 2021). Here, we briefly summarize its core features. As conveyed in Fig. 2, the analysis encompasses five subsystems: (i) agricultural land; (ii) livestock production; (iii) food processing; (iv) food consumption, and (v) residual management. One of the key features of the analysis is the distinction between subsystem components

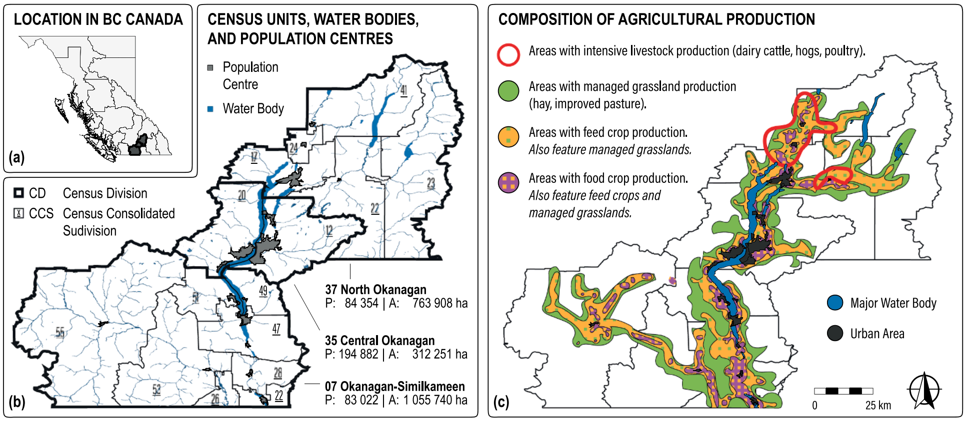
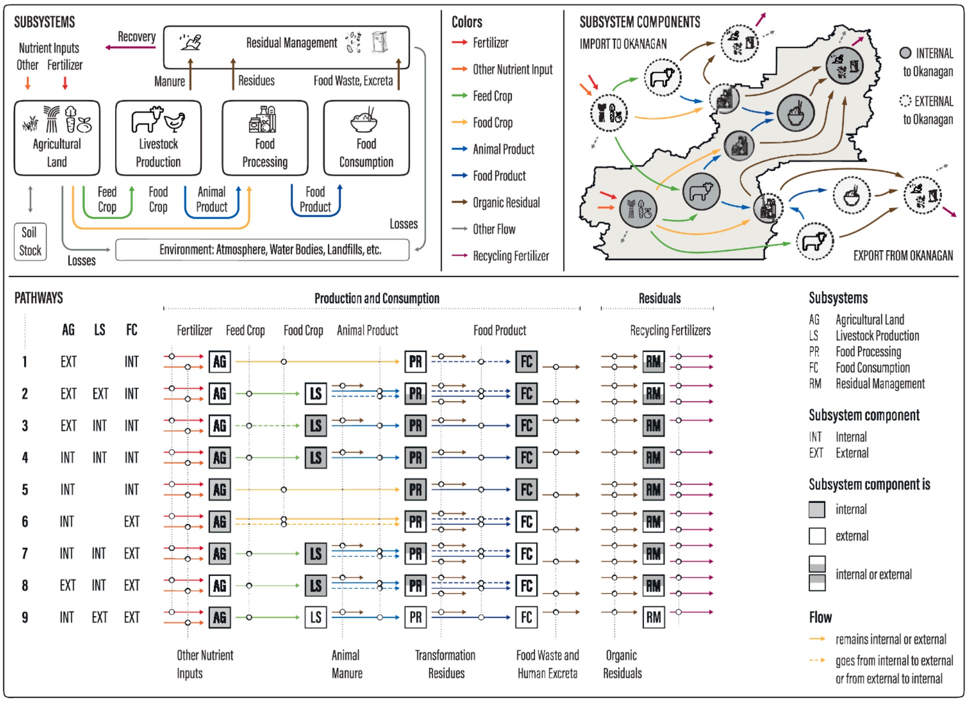


Fig. 1. Overview of the Okanagan bioregion: (a) its location within British Columbia (BC); (b) census units, water bodies, and population centres; and (c) composition of agricultural production.



PATHWAYS	AG	LS	FC
1	EXT		INT
2	EXT	EXT	INT
3	EXT	INT	INT
4	INT	INT	INT
5	INT		INT
6	INT		EXT
7	INT	INT	EXT
8	EXT	INT	EXT
9	INT	EXT	EXT

Fig. 2. Structure of the analysis. For each subsystem, there is one component internal and one external to the Okanagan. For clarity, the external component is split into two parts: one relates to imports into and one to exports from the Okanagan.

considered internal to the Okanagan – representing the bioregional food system – and subsystem components considered external to the Okanagan – representing that part of the global food system with which the bioregional food system interacts through imports and exports of feed and food. Another key feature of the analytical framework is that nutrient flows are disentangled into nine distinct pathways. Each pathway describes a unique combination of where the crop and livestock commodities are produced and the food commodities are consumed. Disentangling flows into pathways makes it possible to track nutrients from inputs to crop production to organic residuals, as a function of where feed and food are produced and consumed.

2.2.2. Definition of nutrient circularity

To enable a more nuanced understanding of nutrient circularity, as conveyed in Fig. 3, we found it useful to distinguish three factors: (i) primary production (i.e. production of grass and crop biomass on agricultural land); (ii) residual management; and (iii) system openness (i.e. how nutrients flow from primary production to residual management as a function of spatial production and consumption patterns).

Separate consideration of the fate of nutrients in primary production allows to understand nutrient use efficiency as a function of crop removal, fertilizer inputs, nutrient inputs other than fertilizers, nutrient losses, and changes in soil nutrient stocks. Separate consideration of the fate of nutrients in residual management allows to understand nutrient recovery efficiency as a function of the type of organic residual and the fate of the nutrients during management. Separate consideration of system openness allows to understand how commodity trade translates into an increased availability of nutrients in organic residuals in one place while reducing availability elsewhere. Note that system openness does not say anything about the leakiness of the system in terms of nutrient losses to for instance landfills and water bodies. System openness simply indicates the extent to which nutrient inputs in one place become available in residuals in another place.

Nutrient use efficiency in primary production and nutrient recovery

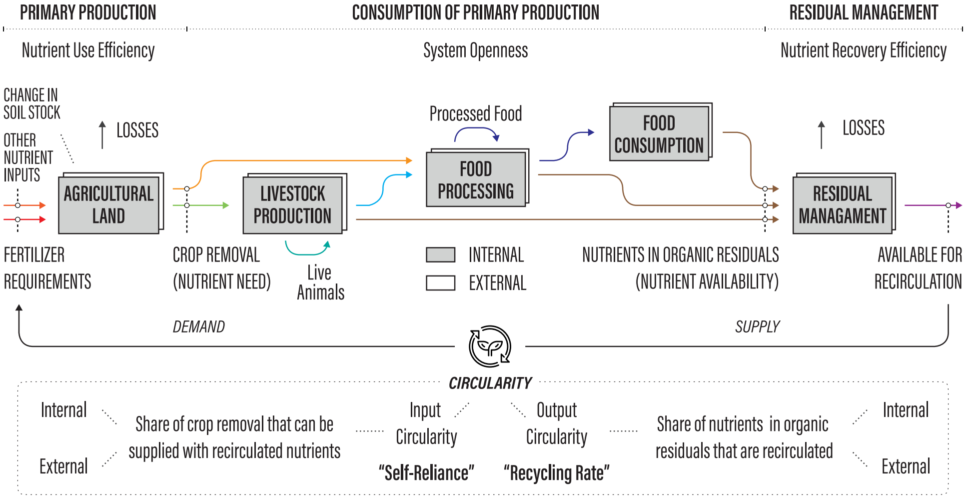


Fig. 3. Nuanced analysis of nutrient circularity. Adapted from (Harder et al., 2021).

efficiency in waste management have been considered separately in previous studies that dealt with nutrient circularity in a given area (e.g. Mehr et al., 2018). Our framework adds the distinction of subsystem components that are internal and external to the area being considered – in our case the Okanagan bioregion. In this way, it becomes possible to expand the analysis of circularity beyond the spatial boundaries of the Okanagan. Insofar as nutrient flows relate to food consumption and production in the Okanagan food system, nutrient circularity can also be assessed outside its spatial boundaries, in the areas with which the bioregional food system interacts through feed and food trade. This is important because feed and food trade means that nutrient inputs to crop production in the Okanagan may make their way into organic residuals outside the Okanagan, and vice versa. If not accounted for, this may lead to a distorted picture when analyzing nutrient circularity.

As conveyed in Fig. 3, our analysis distinguishes four kinds of nutrient circularity, depending on whether the comparison focuses on outputs (in terms of nutrients in organic residuals) or on inputs (in terms of crop removal), and depending on whether the comparison concerns nutrient circularity internal or external to the Okanagan. Because of commodity trade and differences in agricultural and organic residual management practices, internal and external circularity are unlikely to be at the same level.

2.3. Implementation of the calculation model

The calculation model was implemented as a spreadsheet in Microsoft® Excel for Mac Version 16. In general terms, the calculation model does three things: (i) it estimates commodity flows related to domestic production and consumption, as well as import and export; (ii) it estimates the associated flows of nitrogen, phosphorus, potassium, and magnesium across all subsystem components and separately for each pathway; (iii) it assesses the circularity of nutrient flows both internal and external to the Okanagan.

2.3.1. Estimating commodity flows and nutrient flows

Bioregional food demand was estimated based on food consumption statistics for Canada (step 1 in Fig. 4a). The demand for food commodities (e.g. wheat flour or butter) was then converted into a demand for agricultural commodities (e.g. wheat grain or milk) (step 2 in Fig. 4a). Feed demand was estimated based on a typical feed ration for BC Canada and livestock numbers for the Okanagan (step 3 in Fig. 4a). The production of agricultural commodities in the Okanagan was estimated

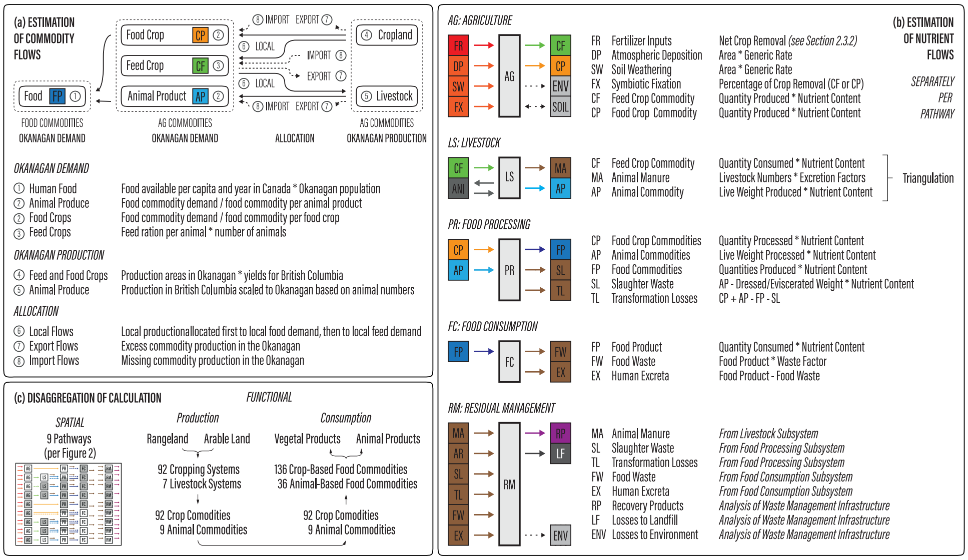


Fig. 4. Procedure for estimating commodity and nutrient flows: (a) estimation of commodity flows, (b) estimation of nutrient flows, and (c) disaggregation of calculations.

based on agricultural statistics for the Okanagan (land use and animal numbers) and yields for BC Canada (steps 4 and 5 in Fig. 4a). But the consumption and production statistics do not reveal which fraction of feed and food produced in the Okanagan is consumed locally or exported, or which fraction of the feed and food consumed in the Okanagan is produced locally or imported. There are also no statistics on feed and food imports and exports at the level of the Okanagan. We therefore had to rely on a set of allocation principles and assumptions. Essentially, local production was assumed to first cater to local demand for human food, then to local demand for animal feed (step 6 in Fig. 4a). Excess production was considered exported and missing production was considered imported (steps 7 and 8 in Fig. 4a). It should be noted that imports and exports are likely greater than estimated this way, but this is not consequential for modeling nutrient flows. For example, it does not matter if 1 kg of apples is imported in spring and 1 kg exported in fall (assuming that their nutrient content is similar). Commodity flow calculations were done separately for 172 food commodities, 92 crop commodities, and 9 animal commodities (functional disaggregation in Fig. 4c).

Commodity flows were then translated into nutrient flows, mostly based on their quantities and nutrient content (Fig. 4b). Nutrient flows were calculated separately for the 9 pathways per Fig. 2 (spatial disaggregation in Fig. 4c). In this regard, it is important to recall that the nutrient flows that lie completely outside the spatial boundaries of the Okanagan were not further specified in terms of their location other than being external to the Okanagan. In this regard, for a few of the nutrient flows, the calculation procedure had to be adjusted. As a guiding principle, we modelled the external component to have technical coefficients similar to the ones used for the internal system. For instance, areas outside of the Okanagan bioregion were estimated based on the quantities of imported agricultural commodities and average yields for British Columbia (for crops also grown in the bioregion) or generally accepted yields (for crops not grown in the bioregion). For livestock production outside the Okanagan bioregion, calculations were based on the quantities of animal product imported to the bioregion and of feed exported from the bioregion, and modelled such that they reflect characteristics representative of the bioregion. Performance and structure of waste management outside the Okanagan bioregion were assumed to be similar to the bioregion.

The procedure for estimating commodity and nutrient flows is summarized in Fig. 4, including equations and allocation rules. Further details are provided in the Supplementary Material.

2.3.2. Assessing the circularity of nutrient flows

Nutrient use efficiency in primary production. Crop removal is rather straightforward to estimate given that areas, yields, and crop nutrient contents are readily available. Fertilizer requirements can be estimated based on recommended fertilization rates, which involves uncertainty, as recommendations may or may not be followed. Another way to estimate fertilizer requirements is through net crop removal before fertilization, that is, removal from crop harvest less soil weathering, atmospheric deposition, and biological fixation. Also this estimate is subject to substantial uncertainty. As a first approximation, in this paper, we used net crop removal as a proxy for fertilizer requirements when assessing nutrient circularity. Based on crude estimates for soil weathering, atmospheric deposition, and biological fixation, net crop removal was estimated to be around 85% of crop removal for phosphorus and potassium, and around 35% for nitrogen and magnesium. We also used the difference between net crop removal and recommended fertilization rates as an indication for changes in soil nutrient stocks.

Nutrient recovery efficiency in organic residual management. Regarding nutrients available for recirculation, we considered two different situations. In the first situation, current recovery rates are assumed, as estimated based on a thorough analysis of the waste management system (see Supplementary Material). In the second situation, which reflects a long-term perspective, we assumed that an overall recovery efficiency of 70% for all nutrients and across all residuals should be feasible. This number reflects a rather ambitious estimate of the recovery rates that full-scale recovery technologies might be able to achieve (a recent systematic review of the effectiveness of struvite precipitation from anaerobic digestate, for instance, found that recovery efficiencies averaged 85% at the laboratory scale (Lorick et al., 2020) – efficiencies at the full scale should be expected to be lower).

System openness. The idea with system openness is that nutrients available in organic residuals are tracked back to where the nutrient inputs to crop production took place. This way, it is possible to see whether the Okanagan benefits from nutrient inputs to crop production outside the Okanagan, and vice versa. System openness was defined as the quantity of nutrients in organic residuals (nutrient availability) divided by the quantity of nutrients removed with harvested crops (nutrient need) – either internal or external to the Okanagan.

3. Results

3.1. Overview of commodity and nutrient flows

To better understand the extent of domestic production and consumption versus imports and exports, we first mapped feed and food flows, see Fig. 5a. Although the Okanagan is one of BC's foremost agricultural regions, overall food self-reliance is low. By weight, about a third of the food consumed in the Okanagan is supplied by local production while the remaining two thirds are imported. Conversely, about two thirds of the feed consumed in the Okanagan is supplied by local production while the remaining third is imported. If feed imports are taken into account, only about a quarter of the food consumed in the Okanagan comes from feed and food crops produced in the Okanagan, while the remaining three quarters come from outside the bioregion or is produced with feed from outside the bioregion. Of course, this pattern has profound implications also for nutrient flows, as exemplified in Fig. 5b for phosphorus.

An alternative representation of phosphorus flows is provided in Fig. 6, which more clearly highlights the high dependence of food consumption in the Okanagan on imports, which means that more nutrient inputs are required external to the Okanagan (FR–SW–DP in boxes 1 and 2). The production of livestock feed is responsible for the majority of the nutrient removal from agricultural land both internal and external to the Okanagan (GR–CF–CP in boxes 1 and 2). The progressive "thinning" of feed and food flows from top to bottom (from FR–SW–DP to FP) indicates that only a very small share of the nutrient inputs make it all the way to food consumption. The rest ends up in organic residuals, notably animal manure. A substantial fraction of the nutrients in organic residuals generated internal to the bioregion originate in crop production outside the bioregion (AM–AR–TL in box 2 and FW–EX in box 3). Nutrients in organic residuals generated external to the bioregion but originate in the bioregion are rather negligible (AM–AR–TL–FW–EX in boxes 4 and 5).

The patterns we map here for phosphorus are rather similar for all nutrients considered. One key difference is that for nitrogen there is significant atmospheric deposition and biological fixation, which means that fertilizer inputs (FR) are relatively smaller while biological nitrogen fixation (FX) and atmospheric deposition (DP) are relatively larger. Also, a comparison across the different nutrients (not shown in the figure) highlights that, compared to nitrogen and phosphorus, potassium and magnesium are more inclined to end up in organic residuals rather than in agricultural and food commodities.

3.2. Fertilizer inputs to agricultural land

As previously stated, there is substantial uncertainty associated with the estimation of nutrient inputs to crop production. Our model considered fertilizer inputs, atmospheric deposition, biological nitrogen

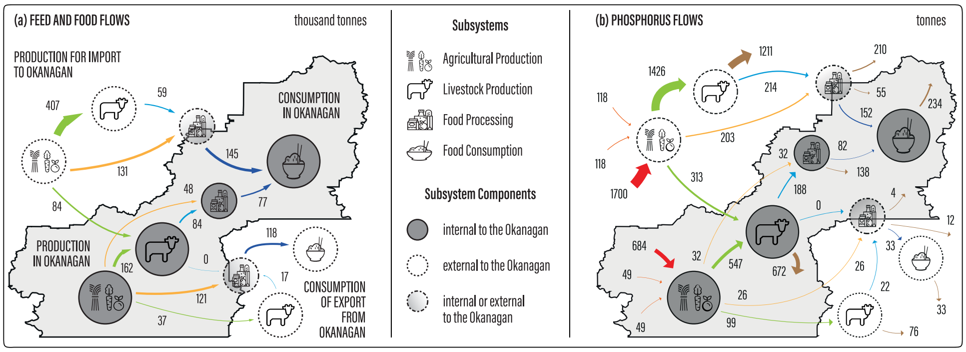


Fig. 5. Feed and food flows (a) and phosphorus flows (b) related to production and consumption in the Okanagan.

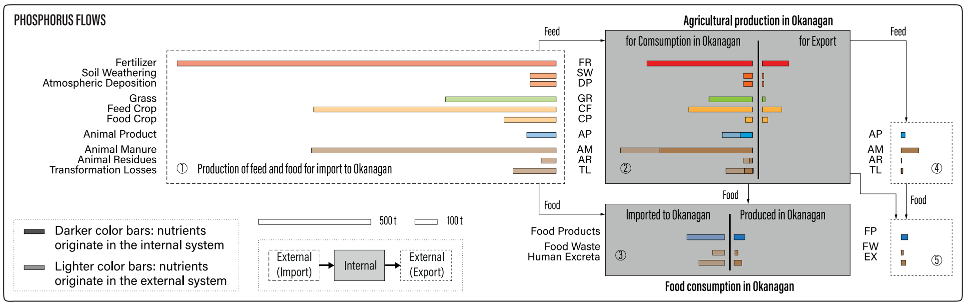


Fig. 6. Alternative representation of phosphorus flows related to production and consumption in the Okanagan.

fixation, and soil weathering. Here, we focus on fertilizer inputs estimated based on recommended fertilization rates for British Columbia. As shown in Fig. 7, recommended nitrogen and potassium fertilization are similar in magnitude. Recommended phosphorus fertilization is about a third of these quantities. Recommended magnesium fertilization is negligible – for many crops there are no recommendations.

A comparison of recommended fertilization rates with net crop removal suggests that nitrogen and phosphorus are essentially balanced, with some losses from cropland being likely to occur. For potassium, fertilization is about half that required for a balance between inputs and outputs – which suggests, in alignment with global patterns, that soil potassium mining might be occurring. For magnesium, it seems that fertilizer inputs are not needed except for a few cropping systems where crop removal exceeds inputs through weathering and deposition. This may explain why for most cropping systems, no recommended fertilization rates are stated for magnesium. Overall, inputs to feed crop production are significantly larger than inputs to food crop production. In both cases, most of the inputs take place outside the Okanagan.

3.3. Nutrients in organic residuals

Nutrients in organic residuals were estimated separately for animal manure and non-manure residuals, see Fig. 7. The quantities of nutrients in animal manure generated internal (solid boxes) and external (dashed boxes) to the Okanagan are roughly similar. Of the animal manure generated internal to the Okanagan, about three quarters originate in the Okanagan food system (dark brown fill) whereas about one quarter originates outside the Okanagan (light brown fill). For residuals other than animal manure, we can see that more nutrients are available in transformation losses (TL) and human excreta (EX) than in animal residuals (AR) and food waste (FW). Animal residuals include streams such a slaughterhouse waste or leaker and reject eggs. Like with manure, the quantities generated internal (solid box) and external (dashed boxes) to the Okanagan are similar in magnitude. Of the non-manure residuals generated in internal to the Okanagan, about half originates in the Okanagan food system (dark brown fill) and about half in outside the Okanagan (light brown fill).

3.4. Nutrient accumulation and depletion as a result of feed and food trade

As conveyed in Fig. 8, for the Okanagan as a whole, nutrient accumulation generally exceeds nutrient depletion for all nutrients. The only exception is potassium, where nutrient accumulation in animal manure is somewhat smaller than nutrient depletion. At the level of individual census units, taking phosphorus as example, for most census units, nutrient accumulation due to feed and food import is larger than nutrient depletion due to feed and food export. The notable exception are some census consolidated subdivisions towards the periphery of the bioregion (e.g. CCS 07 55), where nutrient accumulation and depletion are nearly balanced, or depletion may even exceed accumulation. This is because these areas host significant production of feed for export.

3.5. Nutrient circularity

3.5.1. System openness

System openness is shown in Fig. 9 for the four nutrients considered. Nitrogen and phosphorus are much more mobile across the boundaries of the bioregion, and of individual census areas, than potassium and magnesium. This means that the influence of system openness on nutrient circularity will be different for different nutrients.

3.5.2. Nutrient self-reliance

Nutrient self-reliance is shown in Fig. 10. With current recovery rates, in the Okanagan as a whole, net crop removal of nitrogen and magnesium could be supplied with nutrients recovered from organic residuals, whereas this is not the case for phosphorus and potassium. Within the Okanagan, there would be scope to move some nitrogen, phosphorus and magnesium from the center to the periphery. For potassium, there is a shortage in all census units. As the surplus of nitrogen in the Okanagan comes at the expense of a deficit in the external system, there would also be potential to move some of the nitrogen available in

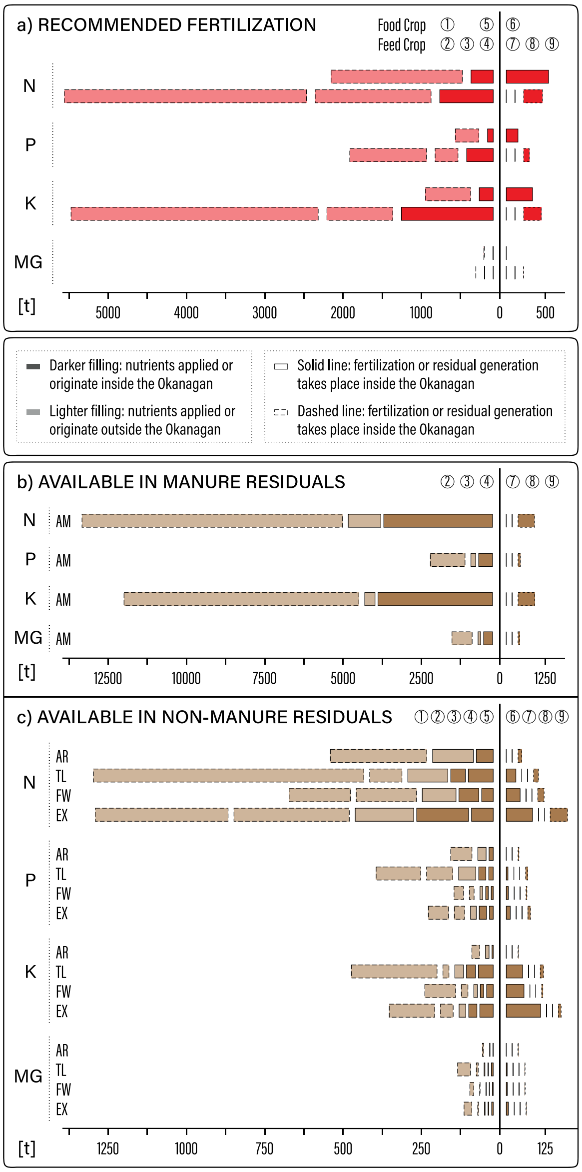


Fig. 7. Nutrients required by crops given the recommended fertilizer rates (a). Nutrients available in (b) animal manure and (c) non-manure residuals. All quantities are shown separately for each of the nine pathways as per Fig. 4 (circled numbers at the top of each sub-figure), and thus represent inputs and availability both internal and external to the Okanagan. Note the differences in scale across the sub-figures.

residuals in the Okanagan outside of the bioregion.

Under the assumptions related to a long-term potential, there would be plenty of nitrogen (due to significant non-fertilizer inputs, notably atmospheric deposition and biological nitrogen fixation) and magnesium (due to significant non-fertilizer inputs, notably soil weathering), both internal and external to the Okangan. Thus there would be no need to move around nitrogen and magnesium outside the bioregion, nor to move within the bioregion. Yet, it would still be important to ensure that nitrogen is managed in such a way that losses of reactive nitrogen to the environment are minimized, so as to minimize harm to ecosystem and human health. For phosphorus, there would be enough available internal but not external to the Okanagan. For potassium, there would be a shortage both in and outside the Okanagan. There would be potential to move some of the phosphorus and potassium in organic residuals from the center to the periphery of the Okanagan. In addition, there would be potential to move some of the phosphorus in organic residuals in the Okanagan outside of the bioregion.

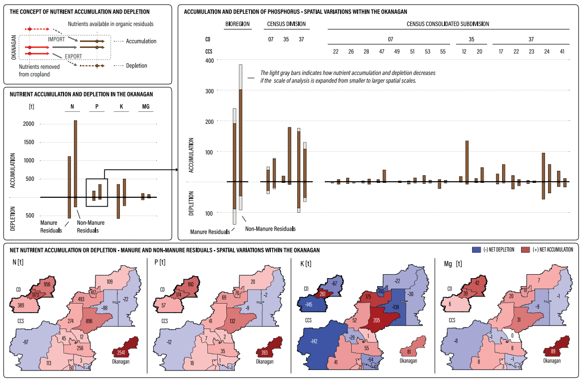


Fig. 8. Nutrient accumulation and depletion for the Okanagan bioregion and its census units (per Fig. 1).

3.5.3. *Relationship between system openness and nutrient self-reliance*

Finally, it is interesting to discuss the relationship between system openness, nutrient self-reliance (i.e. recirculation to the food system), and recycling rate (i.e. recirculation from organic residual management). In this regard, a representation like the one shown in Fig. 11 – again for phosphorus as an example – Fig. 11could be helpful.

If read from left to right (dashed thick arrow), given a certain recycling rate (output circularity), the figure shows the nutrient self-reliance (input circularity) that can be achieved, both internal and external to the Okanagan. An (internal and external) recycling rate of 40% would for instance translate into a nutrient self–reliance of 62% internal to the Okanagan (line P) but of only 31% external to the Okanagan (line P'). This difference is due to system openness.

If read from bottom to top (dotted thick arrow), the figure shows the recycling rate that would be required to achieve a certain desired level of nutrient self-reliance. Thanks to system openness, a desired (internal) nutrient self-reliance of 90% could for instance be achieved with an internal recycling rate of 58% (line P). However, this would imply that nutrient self–reliance would require recycling rates larger than 100% which is simply not possible (line P'). This highlights the need for a higher nutrient recycling rate internal to the Okanagan, so that some of those nutrients can be sent outside the bioregion to compensate for the effects of system openness.

4. Discussion and outlook

As explained in the introduction, this paper builds on a novel analytical framework for identifying and characterizing the pattern of nutrient flows in modern food systems in relation to the level of circularity. This framework is presented in detail in a companion paper in this special issue (Harder et al., 2021). Here, the objective was to describe how we operationalized this framework in a concrete case study, and to showcase its potentiality to analyze the circularity of nutrients flows. Our preliminary application of the calculation methodology focused mainly on the technical aspects of the analysis of the patterns of nutrient flows in a specific bioregional food system. Ultimately, the idea is that this type of analysis can be used to explore how the circularity of nutrient flows is affected by and is affecting: (i) food production; (ii) food processing, storing and distribution; (iii) food consumption, including diets; and (iv) organic residual management.

4.1. *Key findings*

In the Okanagan, feed and food trade with areas outside the bioregion was found to increase the availability of nitrogen and phosphorus in organic residuals in the bioregion by around 50% compared with a

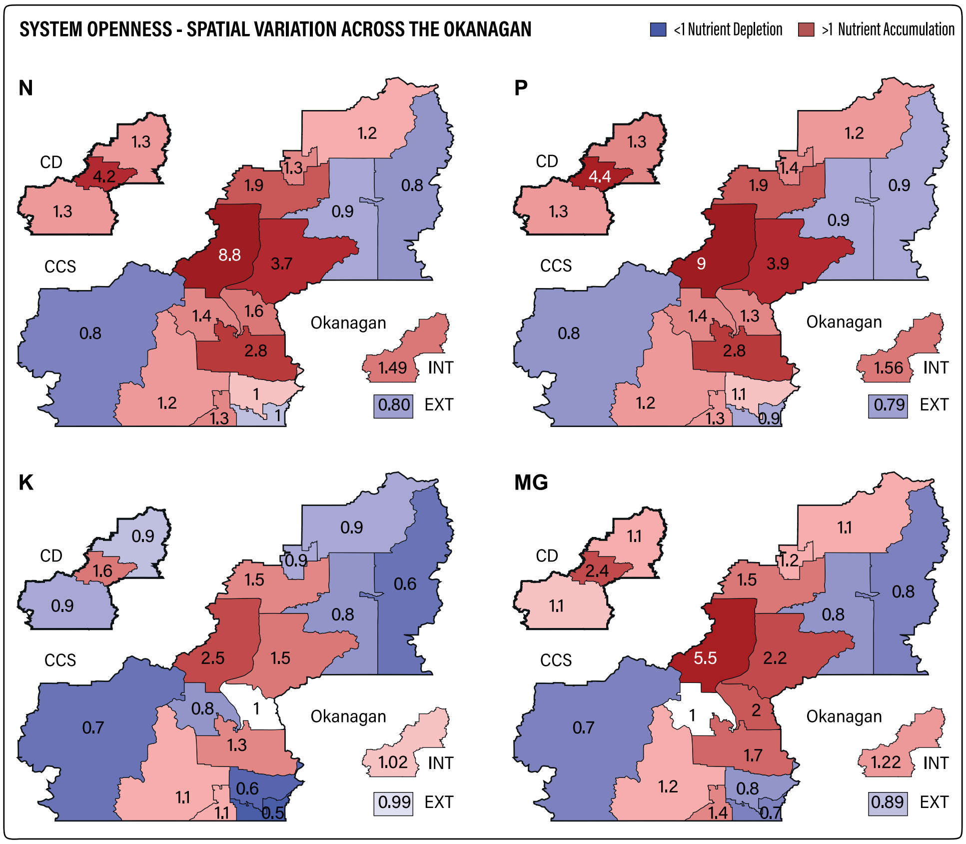


Fig. 9. Spatial distribution of system openness internal to the Okanagan across census units (CD and CCS) (per Fig. 1). At the level of the Okanagan as a whole, system openness is shown both internal (INT) and external (EXT) to the Okanagan.

situation without external trade. For magnesium, with around 20%, this pattern was less pronounced, and for potassium, it did not have an impact. The analysis also suggested that currently, there is a need for new fertilizer inputs for phosphorus and possibly potassium, both internally and externally to the Okanagan. It also suggested a possibility to move some nitrogen in organic residuals outside the bioregion. Under the assumption of a long-term potential for nutrient recovery, only potassium appeared to be potentially critical. This means that it might be a good idea to aim for high recovery efficiencies for potassium. For phosphorus, there would be more than enough available internal to the bioregion, which however comes at the cost of a deficit external to the bioregion. This means that, rather than being satisfied with lesser recovery efficiencies for phosphorus, it would be a good idea to still aim for high recovery efficiencies and make some of the recovered phosphorus available as nutrient input to crop production outside of the bioregion.

4.2. Implications and relevance of the analysis

Global trade of agricultural commodities is generating two serious issues: (i) a food security issue for countries dependent on food imports; and (ii) ethical issues related externalizing environmental and socio-economic stress associated with the production of imported commodities to other countries (Cadillo-Benalcazar et al., 2020; Renner et al., 2020). Our analysis quantified the circularity of nutrient flows with a particular focus on the implications of system openness (in terms of feed and food trade) on managing nutrients in organic residuals.

One way to address the nutrient imbalances that result from system openness would be to minimize system openness. While we acknowledge that there are benefits to re-regionalization of food systems, depending on the spatial scale, this may not always be possible, and in some regards perhaps not entirely desirable or advantageous. For example, in areas that depend on imports, a complete re-regionalization of the food system could necessitate alteration of diet and may compromise food security.

Another way to address the nutrient imbalances would be to send nutrients back to where they came from. However, it is not reasonable to expect that, after the final consumption of either feed or food, the nutrients should go back to exactly the place where the feed and food were produced. If we deem that a certain level of trade among bioregions is necessary or desirable, it thus becomes essential to learn how to monitor and analyze the metabolic pattern of nutrients related to different types of food systems, both internal and the external to the geographical area being considered.

In fact, all else being equal, an increased availability of nutrients in organic residuals internal to the considered area always means decreased availability external to the area, and vice versa. For phosphorus, for instance, our results clearly showed that an increased availability of nutrients in the Okanagan is due to its status of a net importer of feed and food. This comes at the expense of reduced nutrient availability in the places from where feed and food are imported. In other words, while at first sight it may appear that it is acceptable for the Okanagan to operate at lesser levels of phosphorus recovery, the losses of phosphorus are paid for by those who produce the imported feed and food, and who likely have to use more inputs of "new" mineral fertilizers.

This kind of analysis should be useful to communicate to actors in organic residual management the need for comprehensive recovery of some nutrients, even in areas where this is not immediately apparent due to large net imports of feed and food.

4.3. Potential limitations

We are fully aware that the simple rules we devised may not fully

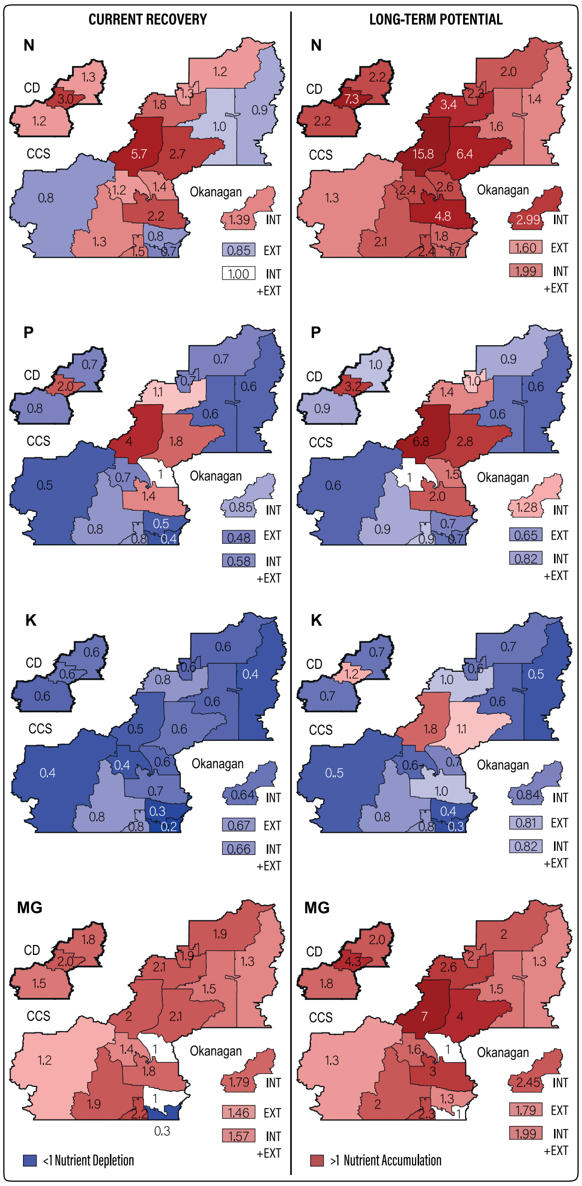
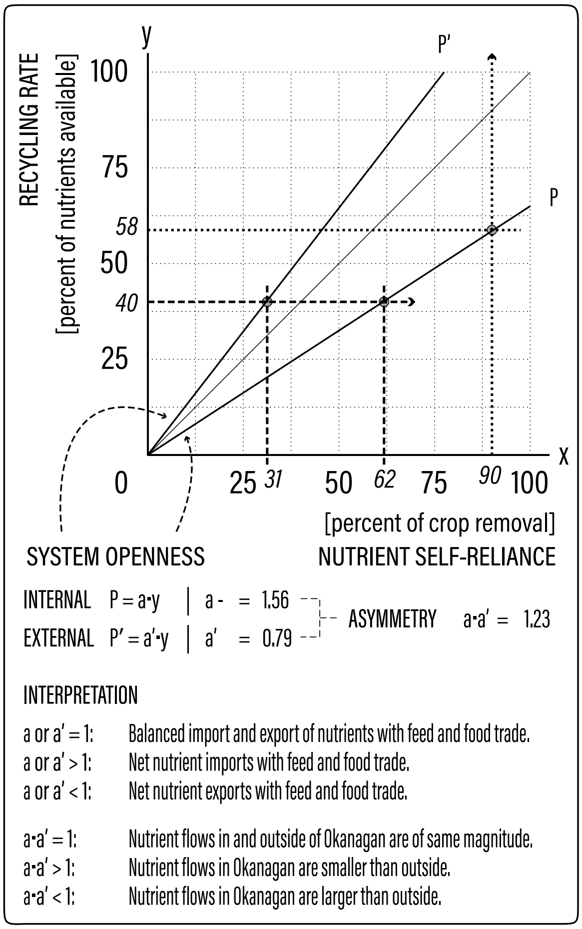


Fig. 10. Nutrient self-reliance across the Okanagan. INT = Internal to Okanagan. EXT = External to Okanagan.



a or a′ = 1: Balanced import and export of nutrients with feed and food trade.
a or a′ > 1: Net nutrient imports with feed and food trade.
a or a′ < 1: Net nutrient exports with feed and food trade.

a·a′ = 1: Nutrient flows in and outside of Okanagan are of same magnitude.
a·a′ > 1: Nutrient flows in Okanagan are smaller than outside.
a·a′ < 1: Nutrient flows in Okanagan are larger than outside.

Fig. 11. Relationship between system openness, nutrient self-reliance, and recycling rate.

reflect the actual situation. For instance, it is known that seasonality constraints imply that domestic production may not actually supply domestic demand (see Dorward et al., 2017). Our allocation rules thus are likely to overestimate the amount of food that is both domestically produced and consumed. But, unlike in the case of food self-reliance, from the point of view of nutrient circularity, it does not matter if for instance apples are imported in spring and the same amount exported in fall (assuming that their nutrient content is similar). Therefore we feel confident that the chosen allocation rules are fit for the purpose of our assessment.

Another potential limitation is that, in our current model implementation, the same technical coefficients (yield, recommended fertilization rates, etc.) are used both internal and external to the Okanagan. This is in part because we lacked data on the origin and destination of imported and exported feed and food, in part because we considered this approximation as good enough for the intended purpose of the assessment. In any case, whenever the origin and destination of imported and exported feed and food are known, like in the study by (Esculier et al., 2019), it would be better to use parameters that more accurately reflect conditions in these places.

The extent of nutrients in transformation losses came as a surprise. In fact, this stream is not usually included in nutrient flow analyses of local agro–food–waste systems. Thus, we either managed to pinpoint a loss that is often neglected, or the conversion factors from agricultural to food commodity that we used are inaccurate, or both. Either way, this aspect deserves to be followed up.

4.4. Potential model refinements

The proposed conceptual framework and calculation methodology seem to be an interesting method to perform nutrient flow analyses. So far, our calculations for the various subsystems followed a rather basic approach, and to some extent were also constrained by data availability. There is ample scope for more refinement by integration with other recent method development. For example, the livestock subsystem could be modelled using a process-based livestock model (Leinonen et al., 2019). There would also be scope to combine the proposed methodology with aspects of transport (Akram et al., 2019; Trimmer and Guest, 2018) and soil suitability (Trimmer et al., 2019a), for instance by positing that the most easily transportable nutrient-rich products are the ones that would most likely go to other regions, and checking how suitable the remaining products are for use in local production. Other possible ways to expand our methodology could be to include carbon flows (Binder and Patzel, 2001; Le Noë et al., 2017), look into long-term trajectories (Bellarby et al., 2018; Le Noë et al., 2018; Spiess, 2011), explicitly consider agricultural trade at the sub–national level (Le Noë et al., 2018, 2017), improve spatial resolution (Leinonen et al., 2019; Metson et al., 2016; Parchomenko and Borsky, 2018), account for plant-availability

(Hamilton et al., 2017) and different fertilization regimes (Hanserud et al., 2016), or consider different waste management scenarios (Wielemaker et al., 2018).

With a view to further case studies, notably such studies that explore food system and waste management scenarios, we believe that the integration of a process–based livestock model, different waste management scenarios, and aspects of soil suitability would be most beneficial.

4.5. Future work

So far, our analysis can be seen as a proof–of–concept that was illustrated with a case study. After some adjustments, it should be possible to apply the analytical framework that was operationalized and illustrated in this paper to study the circularity of nutrient flows not only in food systems, but also in bioeconomy systems more broadly. If this type of approach wants to gain traction to inform policy, it would be important to conduct a thorough sensitivity and uncertainty analysis. This in turn would require building the framework of accounting in a programing language like R or Julia, rather than in a spreadsheet like Microsoft Excel (as done at the moment).

Future work should involve not only a more robust analysis of the metabolic pattern of nutrient flows in the food system, but also an analysis of how this pattern is affected by different typologies of subsystems in the food system – from agricultural to dietary choices to residual management – in different cultures, economic regimes, and geographic areas. This systematization would require building databases and benchmarks organized by typologies of subsystems.

While we are keen to further refine our approach by integration with other recent method development, conversely, we also think that the approach presented here could be meaningfully integrated in other models to extend the scope of analysis beyond the geographical area being considered. Explicitly addressing the effect of system openness is important to assess the entanglement of nutrient circularity locally in the chosen food system, and for the places with which feed and food are traded.

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CRediT authorship contribution statement

Robin Harder: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Project administration, Funding acquisition. **Mario Giampietro:** Writing – review & editing. **Kent Mullinix:** Writing – review & editing. **Sean Smukler:** Writing – review & editing, Supervision.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105842.

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