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Research Brief

From the Okanagan Bioregion Food System Project

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Photo credit: Robin Harder

Nutrient Management in the Okanagan Bioregion

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Abstract

This research brief describes the flows of the nutrients nitrogen (N), phosphorus (P) and potassium (K) related to food production and consumption in the Okanagan bioregion. The focus is on crop nutrient need and nutrients available in organic residuals, as well as how they are influenced by the trade of animal feed and human food. Analysis covers the baseline year 2016 and four food system scenarios in 2050. Findings indicate that better nutrient recovery from organic residuals, such as crop and food residues and animal and human manures, could significantly reduce the need for synthetic fertilizers, both in the Okanagan bioregion and in the regions with which the Okanagan food systems interacts in terms of feed and food trade. Independent of the food system scenario, it would be a good idea to aim for comprehensive nutrient recovery to achieve a more circular use of nutrients in the Okanagan bioregion and other regions.

Executive Summary

Over the past years, growing concern about nutrient pollution of water bodies and future fertilizer availability has emphasized the need for a radical rethinking of nutrient management in all parts of society – from agriculture and food processing to food consumers and waste management. It is in this light that the Okanagan Bioregion Food System Project conducted an in-depth investigation of nutrient flows and circularity related to food production and consumption in the Okanagan.

The focus of the analysis was on comparing nutrient inputs needed to sustain crop production with nutrients available in various types of organic residuals, such as crop and food residues and animal and human manures. To better account for the effect of the trade of animal feed and human food on nutrient need and availability, the scope of the analysis necessarily went beyond the bioregion, to include sources of imported feed and food, as well as the fate of exported feed and food.

Currently, the Okanagan bioregion benefits from nutrient inputs elsewhere – for nitrogen and phosphorus, feed and food trade increases nutrient availability in organic residuals compared to nutrient need in the bioregion by about 50 percent. Due to the projected population increase, this pattern of nutrient accumulation in the Okanagan would be even more pronounced in 2050 across all scenarios. Moreover, spatial variations in agricultural production and human settlements across the Okanagan result in a concentration of nutrients in the more central parts of the Okanagan where population and livestock densities are highest. Thus, nutrients tend to flow not only from outside the bioregion into the bioregion, but also from the periphery of the bioregion towards the center.

With current organic residual management practices and infrastructure, nutrients recovered from organic residuals are insufficient to meet crop nutrient needs in the bioregion. If nutrient recovery efficiency was increased from current levels to 70 percent – which reflects a conservative estimate of the recovery rates that full-scale recovery technologies can be realistically expected to achieve in the long run – there would be a surplus for nitrogen and phosphorus in the bioregion but still a deficit for potassium. But this surplus is because net feed and food imports result in nutrient accumulation in the bioregion. Thus, there is potential to move nutrients not only from the middle to the southern and northern portions of the bioregion, but also outside the bioregion, to at least partially compensate for nutrient depletion external to the bioregion in the places from where feed and food are imported.

Provided that the goal of nutrient management is to maximize nutrient circularity in the Okangan food systems, this will require comprehensive nutrient recovery and re-distribution both within and across the spatial boundaries of the Okanagan. To this effect, even though it may appear that comprehensive nutrient recovery may not be needed in the Okanagan because of substantial availability of nutrients in organic residuals, the analysis we conducted highlighted in quantitative terms that this is to a large extent because of net feed and food imports. In other words, an increased nutrient self-reliance internal to the bioregion comes at the expense of a reduced nutrient self-reliance external to the bioregion. To close nutrient cycles both in the Okanagan and the places from and to which feed and food are imported and exported, comprehensive nutrient recovery is imperative – both for reuse in production in the Okanagan bioregion, but also in those places where the imported feed and food originates. Alternatively, if nutrients are not moved from areas where they are accumulating, they are likely to have adverse environmental impacts and aggravate anticipated future nutrient scarcity.

Background

The Global Nutrient Challenge

Nutrients are Essential for Crop and Livestock Production

Seventeen nutrients are essential for plant growth and development. Overall, the macronutrients nitrogen (N), phosphorus (P) and potassium (K) are required in the greatest quantities. Food crop producers depend on their availability. Livestock production is also dependent on plant nutrients in that their primary source of feed is crops such as grain, silage and pasture.

The Rise of Synthetic Fertilizers

The largest natural reservoirs of phosphorus and potassium are found as minerals in rock and sediment. From there, phosphorus and potassium make their way to agricultural soils through natural processes such as soil weathering and atmospheric deposition, through mining for direct application to crops, or through industrial processing to make synthetic fertilizers. The mining of phosphorus and potassium to enhance food production started in the late 19th century. Nitrogen is abundant in the atmosphere and can be fixed through a symbiotic relationship with microbes, through organic residue mineralization, or through the industrial Haber-Bosch process which produces synthetic nitrogenous fertilizer. The process was invented in the early 20th century and depends on copious inputs of energy and natural gas as a source of hydrogen. Today, production of synthetic fertilizers occurs at such a large scale that nutrient inputs to agricultural soils through synthetic fertilizers exceed inputs through natural processes.

Linearization of Nutrient Flows

The increasing availability of synthetic fertilizers opened the door to increased agricultural production and unprecedented population growth. In places where agricultural production has become more specialized, it is quite common that individual farms, or even entire regions, specialize in the production of specific crops or livestock species. The places where animals consume feed, and generate manure, are thus often disconnected from the places where nutrients are needed for crop production. Similarly, as the world urbanizes, the places where crops are produced are also often disconnected from the places where food is consumed, and food waste and human excreta are generated and must be managed.

These disconnects can make the utilization of organic residuals – notably animal manure, human excreta and food waste – as a source of nutrients to support crop production complicated and expensive. The cost of recovering and utilizing nutrients increases with the distance the residuals have to be hauled, or with the technical processes needed to make them safe to use in crop production or extract and concentrate nutrients so that they can be transported more easily. Often it is cheaper and easier in the short term to supply crops with synthetic fertilizers.

As the world urbanizes, the places where nutrients are needed for crop production are often disconnected from the places where food is consumed. These disconnects can make the utilization of organic residuals – notably human excreta and food waste – as a source of nutrients to support crop production complicated and expensive.

Concerns About Water Quality and Nutrient Security

With current agricultural and organic residual management practices, significant quantities of nutrients are lost from agriculture and other parts of society – for instance, through runoff from agricultural fields or discharges from waste management – that make their way into water bodies, the atmosphere, landfills, and so forth. This has created a number of increasingly pressing challenges to ecosystems and societies around the world.

Nutrient losses to water bodies, for instance, have led to widespread nutrient pollution in freshwater and marine environments, resulting in algal blooms that reduce water quality and may be toxic to plants, animals, and humans. Reliance on nutrients mined from finite reserves is also problematic because existing deposits are declining in both quantity and quality, with the ones remaining often being located in geopolitically unstable regions or becoming more costly to mine due to low concentrations or challenging locations. Costs of mined nutrients are likely to increase as supply dwindles and ultimately becomes scarce. Fluctuating or increasing energy prices, given the direct reliance on fossil fuels for fertilizer manufacturing and transport, are likely to further escalate costs to farmers.

The Need for Closing the Loop

Neither animals nor humans use all of the nutrients in the feed and food they eat, and large quantities of nutrients are therefore excreted. In addition, currently about one third of the human food produced gets wasted prior to consumption. If properly managed and treated, animal manure, human excreta, food waste and other residuals along the food chain can be valuable sources of nutrients for crop production. Over the past years, growing concern about nutrient pollution of water bodies and future fertilizer availability has emphasized the need for radically rethinking nutrient management in all parts of society – from agriculture and food processing to food consumption and waste management. In other words, contemporary agriculture, diets, and waste management practices need to be revised and adjusted so that nutrients are used more efficiently by reducing losses and closing nutrient cycles, as shown in Figure 1.

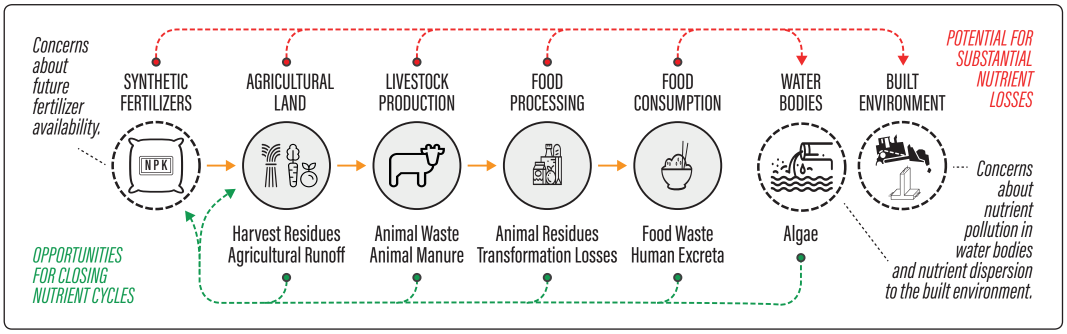

Figure 1: The need and opportunities for closing nutrient cycles.

Aim and Scope

Through an in-depth investigation of nutrient flows related to food production and consumption in the Okanagan, our goal was to conduct an appraisal of current and potential future nutrient flow patterns and associated management options. Ultimately, this entailed a comparison of the nutrient inputs needed to sustain crop production, relative to the nutrients available in various types of organic residuals, notably food waste and residues and animal and human manures.

Like most bioregions, the Okanagan produces animal feed and human food for consumption in and outside the bioregion, and the feed and food consumed in the Okanagan is produced in and outside the bioregion. Due to the trade of feed and food, nutrient inputs to crop production inside the bioregion may make their way into organic residuals outside the bioregion, and vice versa. This may lead to a distorted picture when comparing nutrient need and availability for the bioregion. In this regard, it is worthwhile to note that an increased availability of nutrients in organic residuals generated in the Okanagan always means a decreased availability elsewhere, and vice versa.

To better account for the effect of feed and food trade on nutrient need and nutrient availability, the scope of our analysis went beyond nutrient need and nutrient availability in the bioregion exclusively. Insofar as nutrient flows relate to food consumption (much of which is imported) and production (much of which is exported) internal to the Okanagan bioregion, the analysis also included nutrient need and nutrient availability external to the bioregion.

This research brief describes:

1. Nutrient flows and management for the baseline year 2016 using four nutrient management indicators.
2. How four possible future food system scenarios for the year 2050 compare in terms of these same four nutrient management indicators.
3. The role of organic residual management in closing nutrient cycles in the Okanagan bioregion and beyond.

Methods

Conceptualizing and Contextualizing Nutrient Flows

Our assessment looked at the flows of nutrients related to agriculture and human consumption. As indicated in Figure 2, our conceptual model for nutrient flows related to food production and consumption in the Okanagan consists of the following five subsystems: agricultural land, livestock production, food processing, food consumption, and residual management. It is important to note that, due to feed and food trade, nutrient flows for each subsystem have to be modelled not only inside the bioregion but also outside the bioregion, insofar as they relate to food production and consumption in the bioregion. To this end, we conceptually distinguished between subsystem components that are internal to the Okanagan, and subsystem components that are external to the Okanagan. Subsystem components that are external to the Okanagan represent those parts of the global food system with which the Okanagan food system interacts in terms of feed and food trade.

As shown in Figure 3, settlement patterns and agricultural systems vary across the Okanagan. Therefore, we can expect nutrient flows to vary as well. To explore these variations within the Okanagan, we separately considered the three Census Divisions (CD) and fifteen Census Consolidated Subdivisions (CCS) in the Okanagan.

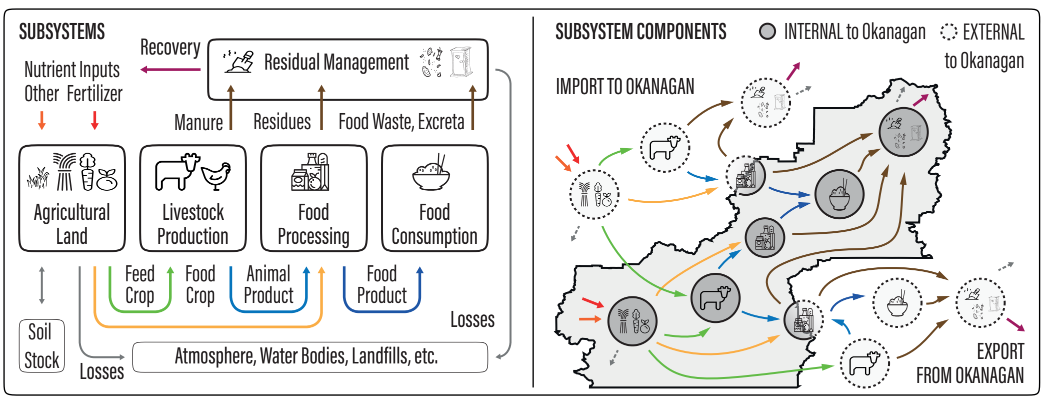

Figure 2: Conceptual model for nutrient flows related to food production and consumption. Note that conceptually, there are no losses in the subsystems livestock production, food processing, and food consumption. Any losses not inherent in forage and crop production take place in residual management.

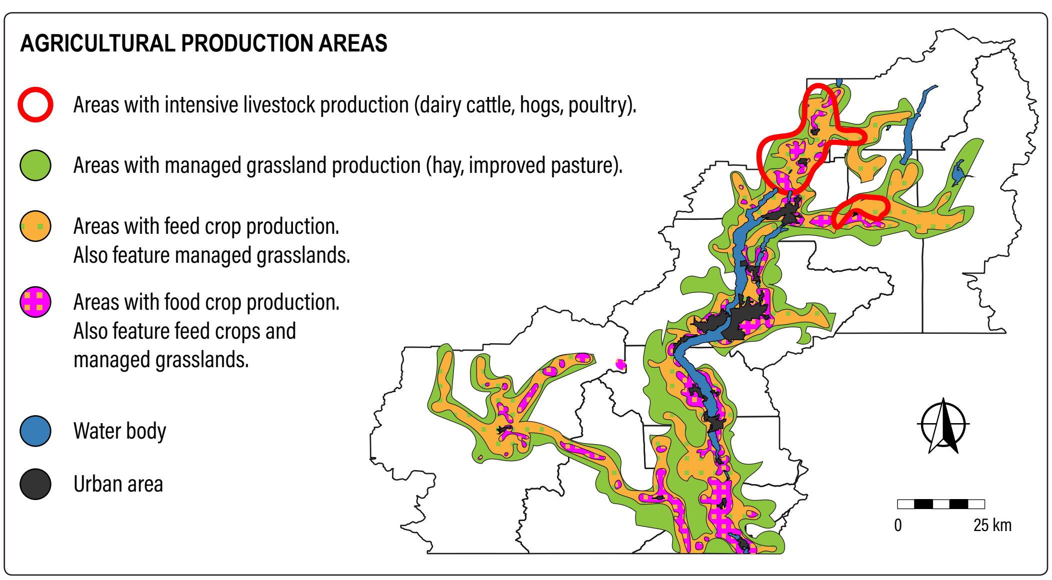

Figure 3: Agricultural production areas and major settlements and water bodies in the Okanagan.

Scenarios

The baseline year was 2016 – the most recent year the Census of Agriculture was conducted. Scenarios were developed for the year 2050 in order to explore various possible futures in terms of the extent of cultivated land, the structure of the food system, and dietary preferences. All scenarios account for a projected population growth in the Okanagan of 40 percent relative to 2016 levels. The four scenarios we explored are summarized in Table 1. For a detailed description of the scenarios, please refer to the Okanagan Bioregion Food System Project summary report.

Table 1: List of scenarios considered. Names as per summary report.

Code	Name	Food System	Year	Diet	Cultivated Land
BAU	Business as Usual	Baseline	2050	Baseline	Baseline
FSR	Regionalized Production	Food Self-Reliance	2050	Baseline	Baseline
EAT	Change Diets	Food Self-Reliance	2050	Planetary Health	Baseline
EXP	Expand Agricultural Land	Food Self-Reliance	2050	Baseline	Expanded (+50%)

Calculations

Step 1: Estimating Feed and Food Flows

The quantity of feed and food production and consumption in the Okanagan was estimated based on agriculture and food statistics available from Statistics Canada. As the scope of our analysis went beyond nutrient need and availability in the bioregion, in addition to local production and consumption, it was necessary to estimate local supply, as well as imports and exports. We could not find any such statistics at the level of the Okanagan and therefore had to rely on a set of allocation principles and assumptions, as described in the following.

Local Demand of Food Commodities

Food consumption in the Okanagan was estimated based on statistics for food available per capita and year in Canada and the Okanagan population. Calculations were done individually for 172 food commodities: 136 based on crop commodities and 36 based on animal commodities.

Local Demand for Agricultural Commodities

Based on generic conversion factors, local demand for food commodities was translated into a local demand for 92 crop and 9 animal commodities. For example, 1 kg of wheat flour requires 1.3 kg of wheat grain and 1 kg of butter requires 12.5 kg of milk. Local demand for animal commodities was translated into a local demand for forage and nine feed grain crops, based on feed requirements to produce a given quantity of animal commodity. For example, 1 ton of milk requires about 80 kg of grass, 200 kg of hay, 370 kg of silage, 290 kg of grain, and 85 kg of oil crops.

Local Production of Agricultural Commodities

Local crop production was estimated based on cultivated areas in the Okanagan and average crop yields for British Columbia. Calculations were done individually for natural and managed pasture, and for 57 crops grown on arable land, ranging from hay and field crops to vegetables, fruits and berries. Local animal commodity production was estimated based on production statistics for British Columbia scaled to the Okanagan based on numbers of animals. Calculations were done individually for 7 livestock systems: dairy cattle, beef cattle, sheep, hog, broiler chicken, layer hen, and turkey.

Estimating Imports and Exports by Matching Demand and Supply

By matching demand from local consumption with supply from local production, we estimated imports and exports. Local production was first allocated to satisfy local demand for food, then local demand for animal feed. Local production that exceeded local consumption was considered exported. Local consumption that exceeded local production was assumed to be imported.
It should be noted that imports and exports are likely greater than estimated, but this is not consequential for modelling 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).

Step 2: Mapping Nutrient Flows

Once feed and food flows were established, the next step was to estimate how feed and food flows coincide with nutrient flows.

Agricultural Land

For agricultural land in the Okanagan, calculations were done individually for natural and managed pasture as well as for 92 crops grown on arable land, including field crops, vegetables, and tree and small fruits. For agricultural land outside the Okanagan, an additional 38 crops not grown in the Okanagan were considered. Nutrient flows were estimated as follows.

- **Crop removal:** nutrient content of the crops and quantities of harvestable crop produced in the Okanagan or imported from outside the Okanagan.

Cultivated areas in the Okanagan bioregion for the baseline were reflective of the 2016 Census of Agriculture. For the EXP scenario that involves an expansion of cultivated land, the same increase was applied to each crop. Areas outside of the Okanagan were estimated based on the quantities of imported agricultural commodities and average yields for British Columbia (for crops also grown in the Okanagan) or generally accepted yields (for crops not grown in the Okanagan).

Livestock

Livestock systems both in and outside the Okanagan were modeled such that they reflect characteristics representative of the Okanagan. Nutrient flows were estimated as follows.

- **Feed:** animal numbers, typical feed ration in BC, and nutrient content of feed commodities.
- **Animal manure:** animal numbers and nutrient excretion factors as per the literature.
- **Animal products:** quantities produced and nutrient content of animal products.
- **Slaughterhouse refuse:** percentage based on difference between live and dressed weight.
- **Other refuse:** percentage based on production statistics for BC scaled to the Okanagan.

Estimates of nutrient intake through feed and nutrients excreted in manure were adjusted to reflect that nutrients are neither created nor destroyed in a given livestock system. Livestock numbers in the Okanagan for the baseline were based on the 2016 Census of Agriculture. For the scenarios, livestock numbers align with the quantities of animal products as per the respective food system scenario calculations (see Okanagan Bioregion Food System Project summary report). For livestock production outside the Okanagan, calculations were based on the quantities of animal product imported to the Okanagan and of feed exported from the Okanagan.

Food Processing and Consumption

Calculations were done for 172 food commodities. Nutrient flows were estimated as follows.

- **Agricultural commodities:** quantities that enter food processing and their nutrient content.
- **Food commodities:** quantities that leave food processing and their nutrient content.
- **Transformation losses:** difference between agricultural and food commodities.
- **Food waste:** food waste factors for individual food commodities for Canada.
- **Human excreta:** nutrients in available food less what is wasted prior to consumption.

Regarding transformation losses, as there are no statistics about what fraction of agricultural commodities is processed in or outside the Okanagan, we assumed that food produced and consumed in the Okanagan is processed entirely in the Okanagan. For food imports and exports, 70 percent was assumed to be processed prior to its import or export.

Waste Management

Calculations were done individually for five organic residuals: animal manure, animal refuse, transformation losses, food waste, and human excreta. Nutrient recovery efficiencies were estimated as follows.

- It is difficult to know what portion of **animal manure** is effectively returned to crop production. This is because there is neither centralized infrastructure for manure management, nor reliable statistics. Assuming that manure is generally adequately managed but transport over larger distances is limited, an overall utilization of 40 percent for nitrogen and 60 percent for phosphorus and potassium was assumed.

- As of 2016, municipal solid organic waste mostly ended up in landfills – except for home composting and a few other composting schemes. It is thus reasonable to assume that most nutrients in **animal refuse** (such as deaths, slaughterhouse waste, and egg refuse), **transformation losses** (processing, adding value), and **food waste** are lost to landfills and the environment. However, planning and implementation of separate food waste collection is under way in the Okanagan bioregion.
- Regarding the fate of nutrients in **human excreta**, as of 2016, about 60 percent of the Okanagan population was connected to a central sewer system, with the remaining population being served by on-site septic systems. Overall, for phosphorus, about two thirds is likely to be returned to crops after biosolids land application. For nitrogen and potassium, the respective fraction is likely about one third and one sixth, respectively.

Recovery efficiencies with current waste management practices are summarized in Table 2. Performance of residual management outside the Okanagan was assumed to be similar.

Residual	Unit	N	P	K
Animal manure	[%]	40	60	60
Animal and food processing refuse	[%]	0	0	0
Food waste	[%]	0	0	0
Human excreta	[%]	35	66	17

Table 2: Current nutrient recovery efficiencies for various residuals in the Okanagan.

Step 3: Nutrient Management Indicators

Mapping nutrient flows with the level of detail described above allows for a nuanced analysis of how nutrients flow through the various subsystems internal and external to the Okanagan. Yet a comparison of food system scenarios from a nutrient management point of view becomes more meaningful if it is based on a suite of indicators that are derived from these nutrient flows, and that summarize key characteristics of relevance to nutrient management. For the purpose of assessing food system scenarios – and keeping in mind the goal of closing nutrient cycles in the bioregion and beyond – we focused on the following four indicators for comparison of scenarios.

Nutrient Need for Crop Production

Nutrient need represents the quantities of nutrients that are generally associated with satisfactory crop growth and development. We distinguished gross and net nutrient need. Gross nutrient need is determined by the amount of nutrients contained in crops harvested for feed and food. This can be otherwise described as crop harvest removal. Upon harvesting, a portion of the crop may remain on the field as crop harvest residue. Our estimation of gross nutrient need did not include this portion, as it is considered in-field nutrient recirculation. Net nutrient need refers to the quantities of nutrients that need to be applied with fertilizers so that the cropping system is in balance in terms of nutrient inputs and outputs. Nutrient inputs other than through fertilizers (symbiotic nitrogen fixation, atmospheric deposition, and soil weathering), nutrient losses, and changes in soil nutrient stocks are inherently variable and uncertain, however. Therefore, we did not quantify net nutrient need. Instead, gross nutrient need was used as a proxy for both fertilizer requirements and nutrient losses from crop production.

Nutrient Availability in Organic Residuals

Gross nutrient availability represents the quantities of nutrients that are contained in animal manure, animal refuse, transformation losses, food waste, and human excreta. Net nutrient availability refers to the quantities of nutrients in organic residuals that are recovered in the current waste management infrastructure as per Table 2, or that could reasonably be recovered with best available recovery technology. In this regard, we assumed that an overall recovery efficiency of 70 percent for all nutrients and across all organic residuals should be feasible. This number reflects a conservative estimate of the recovery rates that full-scale recovery technologies can be realistically expected to achieve.

System Openness

Feed and food trade means that nutrient inputs in one place may make their way into organic residuals in another place. This may lead to imbalance in nutrient availability in relation to nutrient needs, both internal and external to the Okanagan bioregion. We conceived of system openness as the degree to which consumption and trade of feed and food move nutrients from agricultural land in one place to organic residuals in another place. To better conceptualize system openness, we introduced what we refer to as nutrient accumulation and depletion. Nutrient accumulation refers to nutrients that are available in organic residuals in the Okanagan, but that originate from nutrient inputs utilized elsewhere, and subsequently make their way into the bioregion through imported feed and food. Nutrient depletion refers to the opposite, see Figure 4.

System openness was calculated as the quantity of nutrients available in organic residuals (gross nutrient availability) divided by the quantity of nutrients removed with crops harvested (gross nutrient need). 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 cropland equals nutrients available in organic residuals, and system openness thus equals 1. Numbers larger than 1 indicate a net nutrient accumulation, numbers smaller than 1, a net depletion. Thus, system openness represents a measure of the dependence of the Okanagan food system on nutrient inputs to cropland elsewhere, or vice versa.

Nutrient Self-Reliance

This indicator reflects the extent to which nutrients recovered from organic residuals are sufficient to sustain crop production in the long run. As illustrated in Figure 4, nutrient-self reliance is determined by three factors: the fate of nutrients in crop production, system openness, and the fate of nutrients in organic residual management.

Ultimately, it would be desirable to compare net nutrient availability with net nutrient need. But given the high variability and uncertainty regarding the fate of nutrients in crop production, here we instead compared net nutrient availability with gross nutrient need. Yet one has to bear in mind that, in reality, depending on the extent of nutrient losses and inputs through other sources, net nutrient need may significantly deviate from gross nutrient need in either direction. If gross nutrient need exceeds net nutrient availability, this points to incomplete nutrient recovery from organic residuals and/or a significant net export of feed and food. If net nutrient availability exceeds gross nutrient need, this points to a significant net import of feed and food.

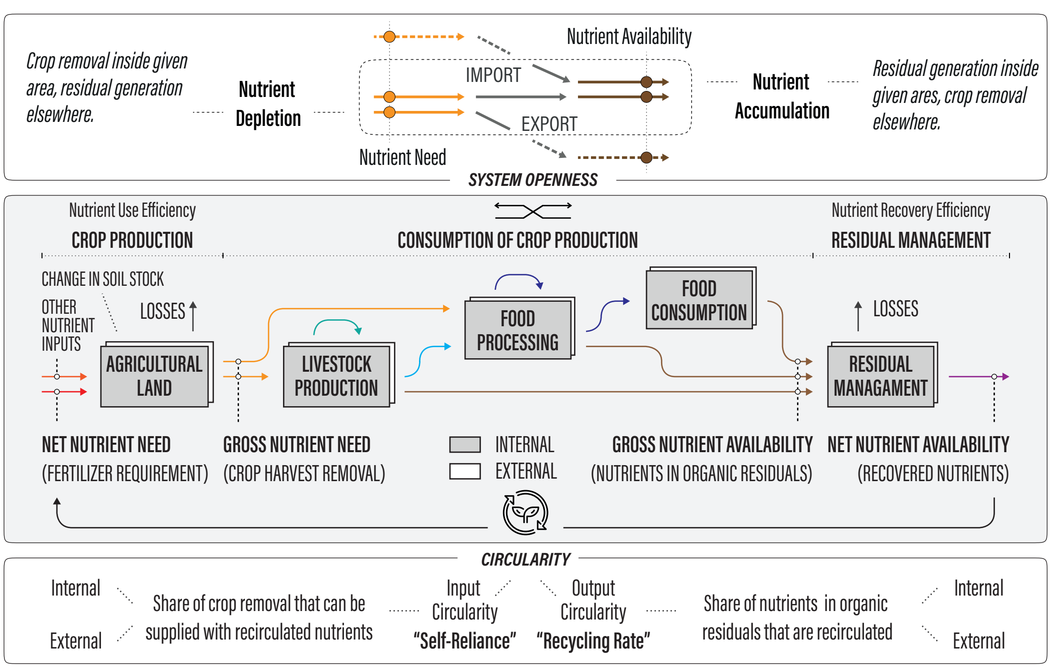

Figure 4: The concepts of nutrient need and availability, system openness, nutrient accumulation and depletion, nutrient self-reliance, and the relationships between them.

The Baseline Year 2016

Feed and Food Flows

Food and feed flows related to Okanagan bioregion food production and consumption are shown in Figure 5. By weight, just over half of the crops produced in the bioregion are feed crops for animals and just under half are food crops for human consumption. The majority of the food crops are exported whereas the majority of the feed crops satisfy bioregion demand. In total, just under half of the crops produced in the Okanagan are exported and just over half satisfy bioregion demand.

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.

Nutrient Flows

Nutrient flows related to Okanagan food production and consumption are shown in Figure 5 for phosphorus as example. Two distinct patterns emerge. First, crop nutrient removal external to the Okanagan bioregion exceeds crop nutrient removal internal to the Okanagan bioregion. Second, even though nutrient flows from livestock production inside and outside the Okanagan to food consumption in the Okanagan are similar, nutrient flows with feed and manure outside the Okanagan bioregion are significantly larger than in the bioregion. This is because there is a larger proportion of meat and a smaller proportion of dairy in imported food (meat production requires more feed and produces more manure per kilogram of produce).

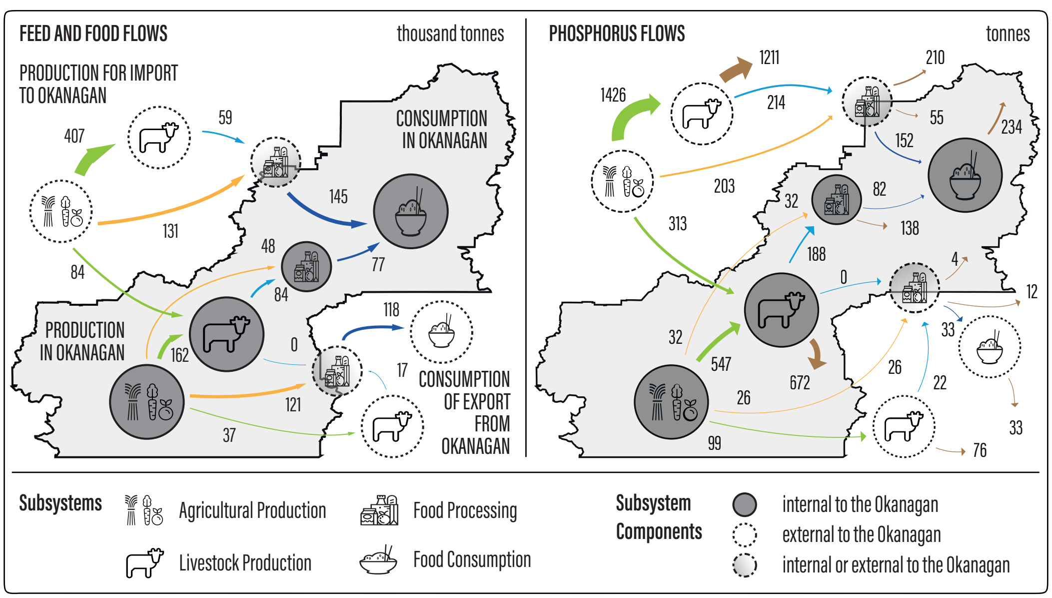

Figure 5: Feed, food, and phosphorus flows related to production and consumption in the Okanagan for the baseline year 2016. Note that the import and export flows reported herein represent a best-case scenario – in reality local supply likely is smaller and import and export larger. Also note that waste management subsystem components are not shown in this figure.

Nutrient Management Indicators

The four indicators nutrient need, nutrient availability, system openness, and nutrient self-reliance are conveyed in Table 3. The evaluation of system openness shows that feed and food trade increases gross nutrient availability compared to gross nutrient need by about 50 percent for nitrogen and phosphorus, whereas this does not apply to potassium.

Nutrient self-reliance was estimated for current recovery and a realistic long-term potential. At current recovery efficiencies, there would be a clear deficit for all three nutrients considered. The long-term potential shows a surplus for nitrogen and phosphorus but still a deficit for potassium.

Of note, nutrient self-reliance includes the effects of system openness. What this means is that it represents a situation where all nutrients recovered from residuals in the Okanagan are kept in the Okanagan, even when they originate from crop production outside the Okanagan (i.e. nutrient accumulation). Likewise, nutrients recovered from residuals outside the Okanagan, from Okanagan products, are not returned to the Okanagan (i.e. nutrient depletion). If nutrient self-reliance was corrected for system openness, the numbers would look different. In the Okanagan, correcting for system openness would decrease nutrient self-reliance for all nutrients, which is due to the effect of feed and food trade.

		Description	Unit	N	P	K
1		Nutrient need, gross	[t]	5 099	704	4 905
2		Nutrient availability, gross	[t]	7 621	1 095	4 997
		- animal manure	[t]	5 101	672	4 332
		- animal residuals	[t]	196	42	16
		- transformation losses	[t]	395	147	183
		- food waste	[t]	635	73	173
		- human excreta	[t]	1 295	161	294
3	= 2:1	System openness	[-]	1.49	1.56	1.02
		Nutrient availability, net				
4		- current recovery	[t]	2 493	509	2 649
5		- realistic recovery potential	[t]	5 335	766	3 498
		Nutrient self-reliance				
6	= 4:1	- current recovery	[-]	0.49	0.72	0.54
7	= 5:1	- realistic recovery potential	[-]	1.05	1.09	0.71

Table 3: Nutrient management indicators for the baseline year 2016 in the Okanagan.

The Effect of Feed and Food Trade

The Okanagan Benefits from Nutrient Inputs Elsewhere

Per what became apparent by looking at values for system openness in Table 3, feed and food trade means that the nutrient availability in the Okanagan bioregion increases in relation to nutrient need, notably for nitrogen and phosphorus. This inevitably means that, as a consequence of feed and food trade with the Okanagan food system, the global food system in which the Okanagan food system is embedded experiences a decrease in nutrient availability in relation to nutrient need.

To explore the effect of feed and food trade, it is illustrative to assess nutrient self-reliance both internal and external to the Okanagan bioregion food system, separately and combined. Internal nutrient self-reliance is the comparison of nutrient need and availability in the Okanagan bioregion. External nutrient self-reliance is the comparison of nutrient need and availability outside but related to the Okanagan bioregion. Overall nutrient self-reliance refers to internal and external nutrient self-reliance combined, that is, nutrient need and availability that relate to food production and consumption in the Okanagan, irrespective of whether production and consumption are internal or external to the Okanagan bioregion. The results are conveyed in Table 4.

Given that nutrient self-reliance represents a comparison between gross nutrient need and net nutrient availability, overall nutrient self-reliance equals recovery efficiency. Thanks to system openness, internal nutrient self-reliance is larger than 1 for nitrogen and phosphorus. Clearly, this comes at the expense of the external nutrient self-reliance being lower than the respective recovery efficiencies.

Nutrient Accumulation and Depletion per Type of Organic Residual

Another aspect that is worth examining is the net nutrient accumulation or depletion (i.e. nutrient accumulation less nutrient depletion) per type of organic residual. Overall, as shown in Table 5, the Okanagan bioregion has a net nutrient accumulation for all three nutrients and across all types of organic residuals – the only exception being potassium in animal manure,

Description	Unit	N	P	K
Nutrient need, gross	[t]	18 172	2 614	13 960
- Internal to Okanagan	[t]	5 099	704	4 905
- External to Okanagan	[t]	13 073	1 910	9 055
Nutrient availability, net	[t]	12 746	1 832	9 786
- Internal to Okanagan	[t]	5 335	766	3 498
- External to Okanagan	[t]	7 411	1 066	6 288
Nutrient self-reliance	[-]	0.70	0.70	0.70
- Internal to Okanagan	[-]	1.05	1.09	0.71
- External to Okanagan	[-]	0.57	0.56	0.69

Table 4: Internal and external nutrient self-reliance, separately and combined, for recovery efficiencies representing a realistic recovery potential.

where nutrient depletion exceeds nutrient accumulation. The reason is that more potassium is exported with feed than imported, and that the majority of potassium is excreted with animal manure rather than incorporated in animal product.

Variations Across the Okanagan

Spatial variations in system openness for manure and non-manure residuals across the Okanagan bioregion are shown in Figure 6, separately and combined. System openness has more pronounced peaks for non-manure residuals than for manure residuals. This can be expected because net food imports in relation to food consumption in the Okanagan bioregion are larger than net feed imports in relation to feed consumption in the Okanagan.

Description	Unit	N	P	K
Total net benefit or cost	[t]	2 568	396	114
- animal manure	[t]	838	122	-110
- animal residuals	[t]	123	25	11
- transformation losses	[t]	241	99	43
- food waste	[t]	463	49	75
- human excreta	[t]	904	103	95

Table 5: Net nutrient accumulation (+) or depletion (-) for the Okanagan, for recovery efficiencies representing a realistic recovery potential.

Implications for Nutrient Recovery and Reuse

Broadly speaking, the patterns in Figure 6 suggest that nutrients are concentrated in the more central parts of the Okanagan where population and livestock densities are highest. In other words, nutrients tend to flow from the periphery of the bioregion towards the center, but also from outside the bioregion into the bioregion. Thus, there is potential to move nutrients from the middle to the southern and northern portions of the bioregion, and potentially even outside the bioregion. This finding is reinforced by the patterns of internal and external nutrient self-reliance as shown in Table 4. From the perspective of better nutrient recirculation both internal and external to the Okanagan bioregion – at higher recovery efficiencies, a portion of the nitrogen and phosphorus that are recovered ought to be sent outside the bioregion. Of course, if overall nutrient recovery efficiency is low – as currently is the case – this is unlikely to happen because all nutrients currently recovered in the Okanagan can be used to satisfy demand by crop production in the bioregion. In this light, our analysis stresses the need for better nutrient recovery even if local demand could be met with lesser levels of nutrient recovery.

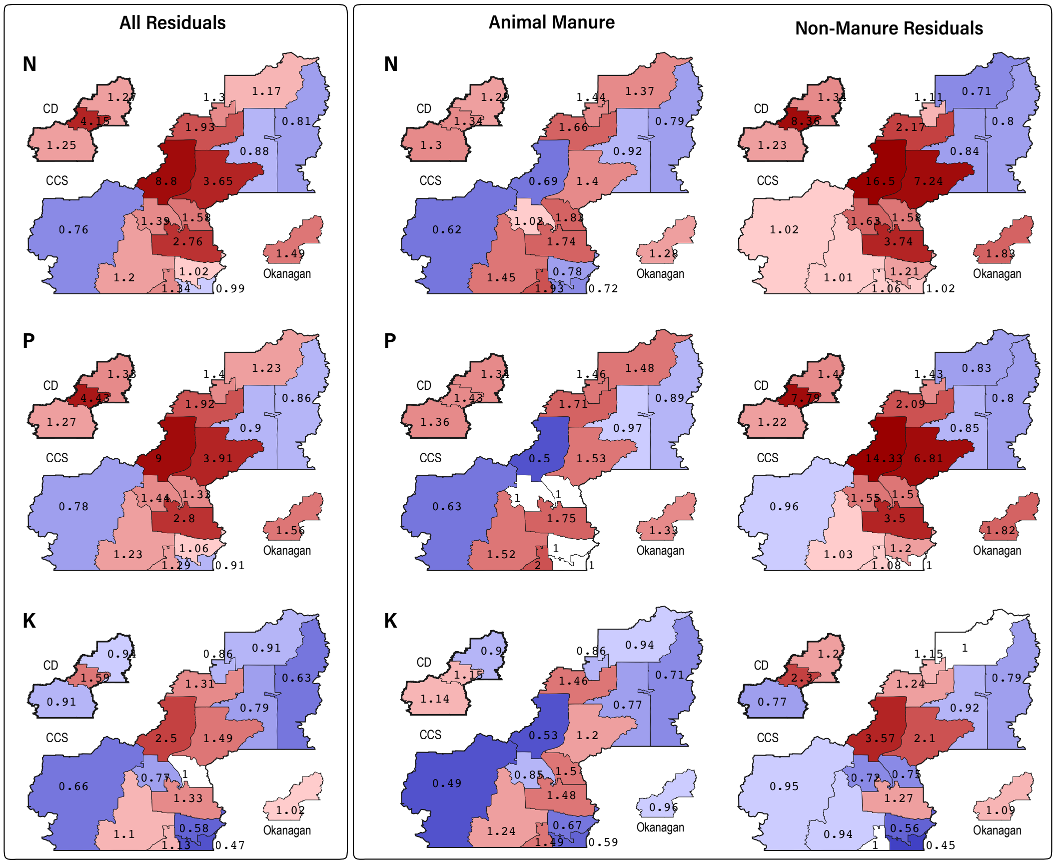

Figure 6: System openness (ratio) across the Okanagan for manure and non-manure organic residuals, separately and combined. Darker red indicates greater nutrient accumulation and darker blue, greater nutrient depletion. Areas in white are in balance.

Food System Scenarios for 2050

The aim here is to discuss how different food system scenarios influence the four nutrient management indicators considered in our study: nutrient need, nutrient availability, system openness, and nutrient self-reliance.

Nutrient Management Indicators

Nutrient Need and Availability

Gross nutrient need and availability, internal and external to the Okanagan bioregion, and relative to baseline (BAS) and business-as-usual scenarios (BAU), are shown in Table 6. All scenarios except BAU reduce internal nutrient need. For the scenarios that model a regionalized food production system, this is because of a shift to crops with lower yields (which means lesser nutrient need). Note that for farmland expansion (EXP), internal nutrient need is higher than for the other regionalized food production scenarios because of expanded food production in the bioregion. The projected population increase in the Okanagan leads to increased external nutrient need for all scenarios except for the planetary health diet (EAT) where external nutrient need is significantly reduced due to lower feed requirements for livestock. For the scenarios that are based on the baseline diet, external nutrient need is only slightly larger than for BAU.

Regarding nutrient availability, there are three overlapping patterns. First, nutrients in organic residuals increase to a degree that reflects population increase in the Okanagan from 2016 to 2050. This pattern is more pronounced outside the bioregion, where most of the additional food is produced. Second, dietary change reduces nutrients in organic residuals due to the lower livestock production requirements to satisfy the diets. Again, this pattern is more pronounced outside the bioregion, because reductions in the consumption of livestock products in the Okanagan lead to a much-reduced need for imported livestock products. Third, the increase in livestock production in EXP means more nutrients in organic residuals inside the bioregion.

System Openness

System openness across scenarios is shown in Table 7. What is interesting is that system openness increases with the scenarios in the FSR family (i.e. FSR, EAT, EXP). This is because optimization for food self-reliance did not feature a constraint that feed needs to be local. In other words, livestock produced in the Okanagan with imported feed was considered local production. As a result, the optimization for food self-reliance led to significantly increased livestock numbers in the Okanagan bioregion along with significantly increased feed imports.

Scenario	Internal		External	
Nutrient need, gross				
BAS	**1.00**	1.00	**1.00**	0.63
BAU	1.00	**1.00**	1.58	**1.00**
FSR	0.53	0.53	1.99	1.26
EAT	0.48	0.48	0.66	0.42
EXP	0.86	0.86	1.96	1.24
Nutrient availability, gross				
BAS	**1.00**	0.91	**1.00**	0.62
BAU	1.10	**1.00**	1.61	**1.00**
FSR	1.24	1.13	1.73	0.95
EAT	0.76	0.69	0.53	0.33
EXP	1.38	1.26	1.76	0.96

Table 6: Changes to nutrient need and availability, internal and external to the Okanagan food system, and relative to BAS and BAU. Numbers represent an average over all three nutrients considered (NPK).

Nutrient Self-Reliance

Nutrient self-reliance is shown in Table 8. With current recovery efficiencies, across all scenarios, nutrients recovered from organic residuals generated in the bioregion would not be sufficient to meet gross nutrient needs except in the FSR scenario. With improved recovery efficiencies, there should be enough nitrogen and phosphorus to meet gross nutrient need in the bioregion. For potassium this pattern only applies to the scenarios based on food self-reliance (FSR, EAT, EXP). External nutrient self-reliance is below 1 across all nutrients and scenarios.

Scenario	N	P	K
BAS	1.48	1.54	1.01
BAU	1.66	1.73	1.06
FSR	3.58	3.77	2.07
EAT	2.36	2.18	1.89
EXP	2.41	2.60	1.46

Table 7: System openness for the Okanagan. Numbers larger than one mean the Okanagan benefits from nutrient inputs to crop production elsewhere more than the other way around.

Sharing Nutrients Beyond the Okanagan

Whenever internal nutrient self-reliance is larger than 1 and external nutrient self-reliance is smaller than 1, there is scope to move nutrients across the boundaries of the bioregion, and at the same time, an increased risk of nutrient losses to the local environment. We estimated the quantity of nutrients that could be moved outside of the bioregion if surplus internal to the bioregion was made available to compensate, at least to some extent, for deficits external to the bioregion, see Table 9.

With current recovery efficiencies, for all scenarios except FSR, there would be nothing to move as there are already nutrient deficits inside the bioregion. But this situation changes drastically with improved recovery efficiencies. Across all scenarios, there is scope to move some of the recovered nitrogen and phosphorus outside the Okanagan.

CURRENT	N		P		K	
Scenario	INT	EXT	INT	EXT	INT	EXT
BAS	0.49	0.30	0.72	0.41	0.53	0.57
BAU	0.52	0.31	0.78	0.43	0.54	0.57
FSR	1.06	0.27	1.47	0.36	0.97	0.52
EAT	0.64	0.24	0.85	0.33	0.68	0.48
EXP	0.72	0.27	1.02	0.37	0.68	0.53
INT+EXT	0.33		0.47		0.53	
IMPROVED	**N**		**P**		**K**	
Scenario	INT	EXT	INT	EXT	INT	EXT
BAS	1.04	0.57	1.08	0.56	0.71	0.70
BAU	1.16	0.59	1.21	0.58	0.74	0.69
FSR	2.50	0.50	2.64	0.47	1.45	0.62
EAT	1.65	0.46	1.53	0.44	1.33	0.58
EXP	1.69	0.51	1.82	0.49	1.02	0.64
INT+EXT	0.70		0.70		0.70	

Table 8: Nutrient self-reliance, internal and external to the Okanagan, for current and improved recovery efficiencies

IMPROVED	N	P	K	N + P + K
Scenario	[t]	[t]	[t]	[t]
BAS	693	136	0	829
BAU	1 334	230	0	1 564
FSR	4 444	729	895	6 069
EAT	1 849	246	415	2 509
EXP	3 303	575	97	3 976

Table 9: Estimated quantities of nutrients that could be moved outside the bioregion to partially compensate for the effect of system openness, for improved recovery efficiencies.

Perhaps counterintuitively, the quantities of nutrients that would need to be moved across the boundaries of the Okanagan to compensate for the effects of system openness would be considerably larger for the FSR scenario family (FSR, EAT, EXP) compared with the baseline and the BAU scenario. Again, the reason lies with the increase of livestock numbers and feed import relative to total production in the FSR scenario family.

Conclusions and Outlook

Our analysis clearly revealed the extent to which the Okanagan bioregion benefits from nutrient inputs elsewhere. In the baseline year 2016, for nitrogen and phosphorus, feed and food trade increases gross nutrient availability compared to gross nutrient need by about 50 percent. This pattern of nutrient accumulation in the Okanagan is even more pronounced for the scenarios that are based on an agricultural system optimized for food self-reliance (FSR, EAT, EXP). This is because optimization for food self-reliance considered livestock produced in the Okanagan with imported feed as local production, and hence did not feature a constraint on feed imports. As a result, the optimization for food self-reliance led to significantly increased livestock numbers in the bioregion along with significantly increased feed imports.

Spatial variations in agricultural production and human settlements across the Okanagan result in a concentration of nutrients in the more central parts of the Okanagan where population and livestock densities are highest. Thus, nutrients tend to flow not only from outside the bioregion into the bioregion, but also from the periphery of the bioregion towards the center.

The comparison of gross nutrient need and net nutrient availability clearly indicated that, with current organic residual management practices and infrastructure, nutrients recovered

from organic residuals are insufficient to meet crop nutrient needs in the bioregion. If nutrient recovery efficiency was increased from current levels to 70 percent, there would be a surplus for nitrogen and phosphorus in the bioregion but still a deficit for potassium. This surplus, however, is thanks to the increased availability of organic residuals in the bioregion that results from net feed and food imports. As a matter of fact, food consumption and production in the Okanagan would still contribute to a nutrient deficit external to the Okanagan. Thus, there is potential to move nutrients not only from the middle to the southern and northern portions of the bioregion, but also outside the bioregion.

In conclusion, even though it may appear that comprehensive nutrient recovery may not be needed in the Okanagan bioregion because of substantial availability of nutrients in organic residuals, the analysis we conducted highlights in quantitative terms that this is to a large extent because of the effect of system openness related to net feed and food imports. In other words, all else being equal, an increased nutrient self-reliance internal to the Okanagan comes at the expense of a reduced nutrient self-reliance external to the bioregion. Thus, if closing nutrient cycles is the goal of nutrient management and the scope includes both the Okanagan bioregion and the food systems from and to which feed and food are imported and exported, comprehensive recovery of nutrients from organic residuals is highly desirable – both for reuse in production in the Okanagan, but also in those places where the imported feed and food originates.

To better close nutrient cycles, both internal and external to the Okanagan bioregion, comprehensive recovery of nutrients from organic residuals is highly desirable – both for reuse in production in the Okanagan, but also to in those places from where imported feed and food originate.

Associated Scientific Publications

Harder R, Giampietro M, Smukler S. **Towards a circular nutrient economy. A novel way to analyze the circularity of nutrient flows in food systems.** *Resources, Conservation & Recycling. Forthcoming.*

Harder R, Giampietro M, Mullinix K, Smukler S. **Assessing the circularity of nutrient flows related to the food system in the Okanagan bioregion, BC Canada.** *Resources, Conservation & Recycling. Forthcoming.*

Harder R, Mullinix K, Smukler S. **Assessing the circularity of nutrient flows across nested scales for four food system scenarios in the Okanagan bioregion, BC Canada.** *Frontiers in Sustainable Food Systems. Forthcoming.*

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About the Institute for Sustainable Food Systems

The Institute for Sustainable Food Systems (ISFS) is an applied research and extension unit at Kwantlen Polytechnic University that investigates and supports sustainable agriculture and regional food systems as key elements of sustainable communities. We focus predominantly on British Columbia but also extend our programming to other regions.

Our applied research focuses on the potential of regional food systems in terms of agriculture and food, economics, community health, policy, and environmental integrity. Our extension programming provides information and support for farmers, communities, business, policy makers, and others. Community collaboration is central to our approach.

About the Okanagan Bioregion Food System Project

Communities and governments are increasingly looking to strengthen regional food systems as a way to address many complex agriculture and food challenges. The Okanagan Bioregion Food System Project explores the social, economic, and ecological outcomes of a regional food system in the Okanagan. This multidisciplinary research project, initiated by ISFS and regional partners, can guide conversations among communities and decision-makers seeking to advance their regional food system.

The Okanagan Bioregion Food System Project considers and builds upon existing food system planning and other related work to support local and regional food systems in the bioregion.

For the full report and more research briefs visit: www.kpu.ca/isfs/okanagan-bioregion

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