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Water, Energy and Nutrient Losses from Food Wastage of Selected Crops in Three Agro-Climatic Zones in British Columbia, Canada

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Abstract

Food waste is a growing global concern. Data on the factors and magnitude are largely global estimates, thus local studies aid in providing information on the impacts of food waste. Three important agro-climatic zones in British Columbia and nine common crops, both annual and perennial, were selected to evaluate the environmental and nutritional implications of local food waste. Using Canadian estimates of total food waste, the constituent water, caloric content, protein, vitamin C, phosphorus and potassium wasted by each crop were estimated. Regionally, the total production and losses were the highest in the Lower Fraser Valley which had high production of potatoes and blueberries, followed by the Okanagan, with grapes and apples, and Vancouver Island, with potatoes. Virtual water was estimated by the BC Agriculture Water Calculator and used to assess the soil and climatic factors impacting the local water demand. Although soil texture seemed to influence water demand, the agro-climatic zone was the main factor controlling the water demand and the corresponding amount of water wasted. Dry agro-climatic zones had annual virtual water up to two times higher for the same crop and soil texture. Lower water demand crops, finer soils and more efficient irrigation systems were more congruent with water stress scenarios. Total losses for each region were based on conservative estimates and would have supplied the caloric energy and protein for over 40,000 adults, and vitamin C for over 300,000 adults for one year. Additionally, the total N, P and K wasted accounted for up to 32, 2 and 13 kg/ha respectively for common fertilizers used in British Columbia. This study confirmed the significance of food waste impacts on local water demand, human nutrition and soil management based on regional data for representative crops.

Keywords

Food Loss, Food Waste, Crop Water Demand, Virtual Water, Nutrition

1. Introduction

Food producers are under increasing pressure from growing populations and climate change to increase sustainable food production and reach equitable standards globally [1] [2] [3]. Recent projections have estimated that food production must increase by up to 62% to meet demand by 2050 when taking climate change into account [4]. Additionally, the Intergovernmental Panel on Climate Change (IPCC) recently reported that warmer and drier conditions compounded by more extreme events are already negatively affecting yields of some crops and causing food system disruptions, especially in drier and lower-income areas [1]. Consequently, local efforts to optimize the food system and minimize inefficiencies are needed to achieve long-term food security [1] [2].

Reducing food loss and waste may contribute to local food security and the more equitable distribution of food, for lower-middle-income and high-income countries alike [5] [6]. Global reports estimate that around 20% - 40% of the total food production ends up being wasted [2] [3]. This has numerous implications from socio-economic and political to environmental and nutritional. According to IPCC estimates, food production accounts for up to 42% of the global greenhouse gas emissions (GHG). Food wastage alone is responsible for almost 10% of those emissions [1] [2] and uses the equivalent of 28% of the global agricultural land area [7]. Additionally, wasted food represents the loss of important sources of nutrients for human nutrition, including vitamins and protein, caloric energy and constituent water [8] [9].

Food loss and waste occur throughout all food sectors, from initial farm production to final household consumption. The main food sectors of the food supply chain (FSC) include; the field; packaging and processing; transportation and distribution; retail; and the final consumers [10]. The environmental impacts progressively increase along with the FSC, as impacts, such as carbon emissions and water use arising from processing and transport, are added to the initial production impact [3]. In Canada, the Value Chain Management Centre estimates that the final consumers are responsible for almost half of the total food wastage (47%) and thus are major contributors to the environmental impacts of food wastage [10].

The Food and Agricultural Organization of the United Nations (FAO) provides three definitions for the waste of food, including 1) food loss, the deterioration of food that was originally intended for human consumption; 2) food waste, as food appropriate for human consumption being discarded and left to spoil; and 3) food wastage (or wasted food), encompassing both [3]. Food loss is more related to the initial food sectors of the FSC, while food waste usually takes place at the retail and final consumer levels [8]. The reasons for food loss and waste differ among sectors, but recent reports concluded that food wastage generation is similar between countries with varying levels of income, with relatively higher waste at the final consumer levels [5].

Agricultural activities also have major implications for water resources management. The amount of water required to produce a product or commodity from start to finish is defined as virtual water [11] [12]. For agricultural products, virtual water includes rainwater and water allocated for irrigation, which is the major contributor to water scarcity [13] [14] [15]. Agriculture alone accounts for almost 70% of the freshwater used around the world, with 24% of that linked to annual wasted food worldwide [16] [17]. Therefore, reducing food wastage is an integral component of improving the management of local water resources [16] [18].

However, virtual water estimations are complex and depend on the crop, local soil conditions, climate, etc. To address this and to help conserve the local water resources for agricultural land use, the Agriculture Water Demand Model was developed for British Columbia (BC), Canada, which provides a useful tool for estimating the virtual water at a local scale [19]. The model calculates the water demand for different crops based on varying water requirements for crop groups [20] [21]; soil conditions, including soil texture and structure which govern water storage and movement [22]; and climate parameters, including precipitation levels during the growing season, evapotranspiration and frost-free days, among others [19].

So, the question arises, what is the driving factor for local water demand? BC is the most agriculturally diverse region in Canada, with different agro-climatic zones supporting the production of over 200 commodities. More than 70% of the total farms in BC are located in southern agro-climatic zones—the Lower Fraser Valley, Vancouver Island and Okanagan [23]. However, the three regions are already facing challenges in managing water demand, especially during the relatively dry growing seasons. Climate change projections estimate that the three regions will show a notable decrease in the summer rain, along with growing populations and increasing urban areas, which will exacerbate the demand for water [24] [25]. Consequently, understanding the water demand dynamics among different climates, soils and crops is important for climate change action plans in these regions.

As recommended by [26] [27] [28], additional information is needed to evaluate the differences and magnitude of local food waste and water demand in relation to the global estimates. In addition, most food waste studies are restricted to either environmental or nutritional implications, and detailed nutritional studies are commonly limited to specific countries and food groups [9] [29]. Reinesch *et al.*, 2022 [30] recently estimated both water and nutrient losses from selected crops in the Lower Fraser Valley, Canada. The present study expands that analysis and assesses local data on food wastage by comparing the results from the Lower Fraser Valley [30] to two additional important agro-climatic zones in BC, Canada.

The objectives of this paper were to:

1) Evaluate the estimated virtual water, constituent water, caloric energy and nutrient losses from food wastage of selected crops in three agro-climatic zones in BC;

2) Compare the changes in water demand among different climates, soil conditions, irrigation systems and crops to provide information that can assist local decision-makers on water resource reallocation and conservation use.

2. Methods

2.1. Study Area

The three regions selected for the study were the Lower Fraser Valley (LFV), Vancouver Island and Coast (VI) and Okanagan (OK), in BC Canada (**Figure 1**). These areas represent the most productive agro-climatic zones, ranging from dry to wet regions within BC. The OK basin is one of the driest in southern Canada, with a semi-arid climate; the LFV is one of the wettest watersheds with a moderate, oceanic climate; and the VI has a temperate-Mediterranean climate (**Figure 2**) [31] [32] [33]. The three study areas are situated in different agro-climatic zones, as they differ in growing degree days, and their variability in precipitation during the growing season is directly related to their irrigation water demand (**Table 1**) [34].

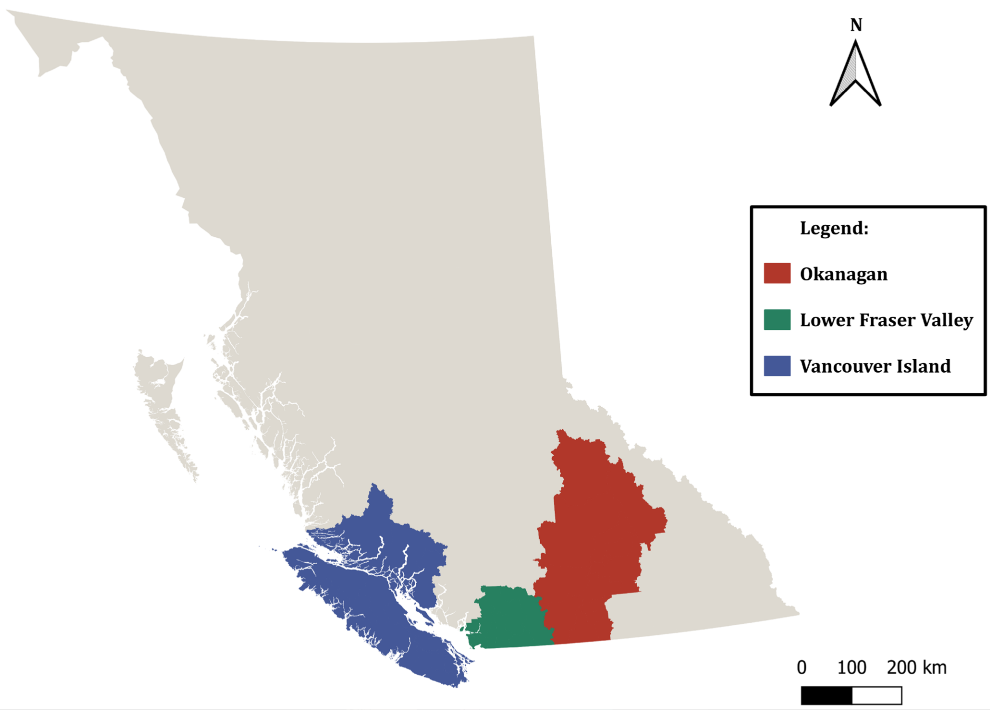

Figure 1. Map of the three study areas in British Columbia, Canada.

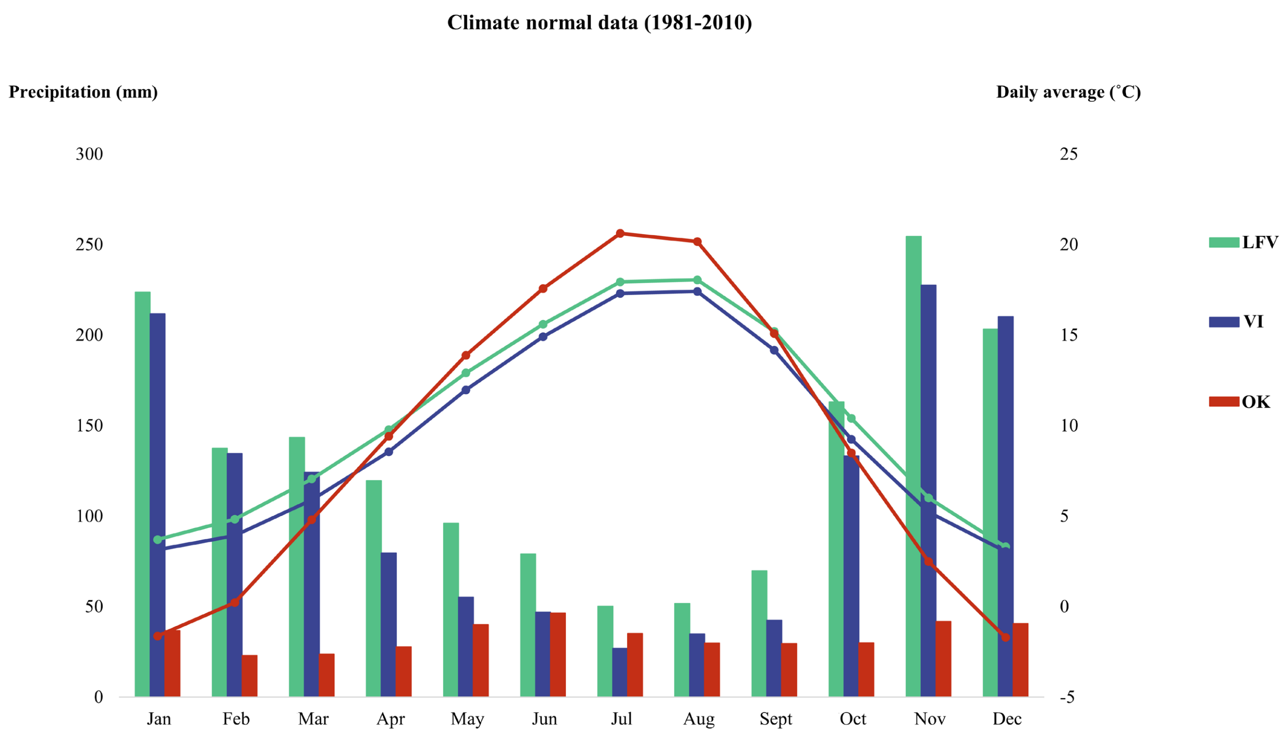

Figure 2. Climate normal data (1981-2010) for the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI). Daily average monthly temperatures (˚C) are shown in the line graph, and average monthly precipitation (mm) values are shown in the histogram for each region. Data obtained from Environment Canada [34].

Table 1. Climate normal data (1981-2010) for the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI) for the growing season and full year. Data obtained from Environment Canada [34].

Variable	Region	Growing season*	Annual
Rainfall (mm)	OK	181.0	323.2
	LFV	465.7	1535.6
	VI	285.9	1270.7
Growing degree—above 5˚C	OK	1937.6	2274.0
	LFV	1844.9	2207.8
	VI	1668.6	1942.9

*Okanagan growing season was considered from May to September. Vancouver Island and the Lower Fraser Valley from April to September.

2.1.1. Okanagan

Agricultural production varies across the OK region and represents 17% of BC's gross farm receipts and 75,160 ha of crop farmland [35]. Most of the agricultural production occurs around Okanagan Lake, including a mix of high-value horticultural crops, beef and dairy products. The south-central areas produce the majority of apples, cherries and grapes in the province, with agriculture as an important economic sector [31]. The region has a semi-arid climate, with 156 frost-free days and a lack of precipitation during the growing season (181 mm of rainfall) (**Table 1**) [34], which creates a high dependence on irrigation and surface water resources [25]. Recent climate change projections estimate that the region can expect 9% less precipitation in the summer by 2050, higher temperatures, more frequent droughts and a longer growing season [31]. The increasing water deficit during the growing season compounded by growing urban and rural populations will raise the water demand in the region in the coming years [25].

2.1.2. Lower Fraser Valley

The LFV, which comprises the Fraser Valley Regional District and Metropolitan Vancouver, is responsible for the largest gross farm receipts (65%) in BC, based on 62,100 ha of crop farmland [35]. Agricultural activity in the region occurs mostly in the Lower Fraser River floodplain, on some of the most fertile soils in Canada [32]. The region's climate and environmental advantages, together with large markets, enable diverse agricultural production in the region [32], including blueberries, cranberries, raspberries, grapes, nursery products, tomatoes, potatoes, pumpkins, green peas, beans, sweet and forage corn [36]. The climate is relatively mild, with the highest average frost-free days in Canada (217 days), and an annual rainfall of 1535.6 mm (**Table 1**) [34]. However, low precipitation during summer creates the need for irrigation (**Figure 2**) [34]. Climate change projections expect that this demand will keep increasing, with a 12% decrease in summer rain by 2050 [32].

2.1.3. Vancouver Island and Coast

The VI has diverse agricultural production, with forage production being the most common. The region shares 5.4% of BC's gross farm receipts and 11% of the total vegetables and nursery products production in the province, based on 18,490 ha of crop farmland [35]. Agricultural production is concentrated in the eastern valleys and lowlands of the island, including beef cattle, dairy, egg and horticultural crops production. From 2011 to 2016, livestock production decreased while the number of vegetable farms increased on the island [33]. The region has 189 frost-free days and 1270.7 mm of annual rainfall (**Table 1**), with long and rainy winters and water deficits during summer (**Figure 2**) [34]. Around 80% of the annual rainfall occurs out of the growing season (**Table 1**) [34] and climate change projections estimate a 13% decrease in summer rain by 2050 and longer periods of dry spells [33].

2.2. Crops and Nutrients Selection

The following crops were selected for the study; blueberry (*Vaccinium corymbosum* L.), raspberry (*Rubus idaeus* L.), strawberry (*Fragaria* × *ananassa* Duch.), potato (*Solanum tuberosum* L.), sweet corn (*Zea mays* L.), pumpkin (*Curcubuta pepo* L.), green peas (*Pisum sativum* L.), apple (*Malus* × *domestica* Borkh.) and grapes (*Vitis vinifera* L.), as they are representative of field crops, fruit trees and berries grown in the OK, VI and LFV. These crops represent a range of both annual and perennial crops that vary in management practices and physiology (e.g., berries, peas and sweet corn aboveground consumables and below ground edibles such as potato).

Nutrients selected included three that a deficiency may be alleviated by soil management, namely plant macronutrients nitrogen (N) (estimated through protein content), phosphorus (P) and potassium (K), and one that is manufactured within the crop or a value-added factor, vitamin C. Constituent water and caloric energy content in the crops were also assessed. Water demand for different irrigation techniques used in the three regions was calculated to show how varied irrigation management can affect water demand for each crop in each different agro-climatic zone.

2.3. Annual Calculations

For each region and crop, the water demand and nutrient content were calculated on an annual basis, as graphically described in **Figure 3** and consistent with the procedures outlined by [30] and [37].

For the soil characteristics, the Soil Management Groups considered were those that could grow the crops selected for analysis in each region (**Table S1**) [38] [39] [40]. Two soil series with different textures were chosen for each group [41] [42] [43] [44]. The number of soil series selected was 18 for the OK, 12 for the LFV and 10 for the VI. For each soil series, one location/parcel identification (ID) given on the BC Soil Information Finder Tool (SIFT) [45] was selected to calculate the water demand (**Figure 3**).

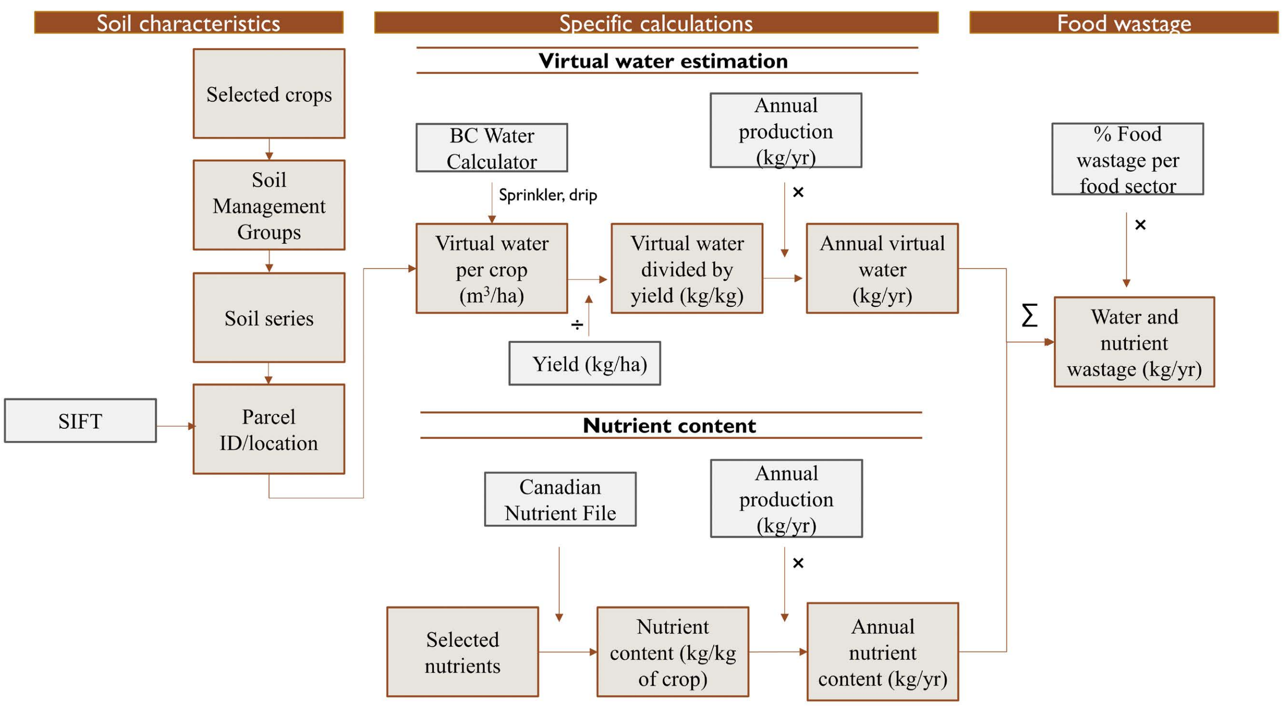

Figure 3. Methodology diagram from the calculations of virtual water, annual nutrient content and food wastage.

For the specific calculations, the parcel IDs were used in the BC Agriculture Water Calculator v2.1.1 [46] as a comparative indicator of the virtual water for each crop, soil series (determined by the soil texture input in the model) and two irrigation systems—sprinkler and drip (**Figure 3**). Sprinkler irrigation refers to a system where water is sprayed into the air onto crops using pumps, hoses, and sprinklers, while drip irrigation refers to a system that slowly dispenses water from irrigation tubes with regular punctures over the crops rooting zone.

The total annual production (kg/yr) for each crop and region was calculated by multiplying yield values (kg/ha) by the harvested areas (ha). Annual yield (kg/ha) from averages of BC Fast Stats data between 2015 and 2019 [36] and harvested areas (ha) from the 2021 Agricultural Census were used in the calculations [47]. The LFV total area was based on the sum of Fraser Valley and Greater Vancouver districts, while the VI area included the total area for all Vancouver Island and Coast districts and the OK the total area for all Thompson-Okanagan districts [35].

To examine virtual water in relation to local yield (kg of water/ kg of crop), the virtual water results from the BC Agriculture Water Calculator (m^3/ha) were divided by the yield (kg/ha) of each crop and multiplied by the density of water (999.07 kg/m^3 at 15.6˚C [48]) (**Figure 3**).

The nutrients, constituent water and caloric energy contents for each crop were based on the Canadian Nutrient File (CNF) [49]. Annual nutrient contents were calculated by multiplying the content per kg of crop by the annual production (**Figure 3**).

2.4. Food Wastage

Annual food wastage was calculated based on an estimate of 30% of total food loss and waste, which is a conservative estimate for Canada [10], and was used in the calculations of nutrient and virtual water losses (**Figure 3**). The annual wastage for the crops considered in the study were compared to daily nutritional guidelines: 2600 kcal/day for 30-year-old males [50]; 64 g/day of protein for 80 kg adults [51] and 90 mg/day of vitamin C [52]. The estimated virtual water losses were compared to the daily residential water use in BC [53]. Fertilizer estimates were based on nutrient content N, P and K in associated common fertilizers in BC. These include ammonium sulfate (20-0-0 24S) and urea (46-0-0) for N fertilizers, monoammonium phosphate (11-52-0) for P fertilizer and potash (0-0-60) for K fertilizer [54]. The total losses were divided by the respective annual nutritional requirements and annual water use to get the number of people per year that could be supplied by the food wastage in the regions, and by the total harvested area to determine the amount of fertilizer that was wasted on the land area.

2.5. Virtual Water Analysis

To examine the driver factor of virtual water, a principal component analysis

(PCA) was completed using the FactoMineR package [55] on soil properties using texture (% sand, silt and clay), organic carbon content (%), soil bulk density, growing season and virtual water for each crop, to assess any variability in these properties inherent in the different regions. Organic carbon, bulk density and soil texture for each soil series were gathered from the SIFT [45].

To examine the return per m^3 of water used in the three regions, the total sales of each crop were divided by the estimated total virtual water. First, the sales rates per ton of crop were calculated by dividing the total farm gate in BC by the BC marketed production in tons [56]. Then, it was converted to sales per kg by dividing by 907.185 kg/ton [57]. The total sales value (M$/yr) in the three regions was calculated by multiplying the annual production of each crop by the sales per kg. Finally, the return per m^3 of water was calculated by dividing the total sales value (M$/yr) by the total sprinkler virtual water (Mkg/yr) times 999.07 kg/m^3 (based on [48]).

3. Results and Discussion

3.1. Annual Production

The LFV had the highest total production of the crops selected (167 million kg), with blueberry and potato showing the two highest production values. The OK was the second highest producer (141 million kg), with grapes and apples as the two highest production values. The VI had the lowest production of the crops selected (16 million kg), with potatoes and apples showing the two highest production values (**Table 2**). The crops selected represent 16% of the total harvested area in the three regions, as the analysis focused on crops for human consumption. Since the three regions show hay and forage as the majority of their agricultural production [35], the impact of food waste and water allocation are potentially much higher than estimated.

Table 2. Agricultural yield (kg/ha) [36], harvested area (ha) [47] and annual production (10^6 kg/yr) for selected crops in the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI).

Crop	Yield (kg/ha)	Area (ha)				Annual production (10^6 kg/yr)			
		OK	LFV	VI	Total	OK	LFV	VI	Total
Blueberry	7752	71	10,694	149	10,914	0.6	82.9	1.2	84.6
Grapes	7839	4713	225	178	5116	36.9	1.8	1.4	40.1
Apple	28,852	3196	43	149	3388	92.2	1.2	4.3	97.8
Potato	34,010	253	1804	186	2243	8.6	61.4	6.3	76.3
Sweet corn	7514	59	666	176	901	0.4	5.0	1.3	6.8
Raspberry	6901	17	744	26	787	0.1	5.1	0.2	5.4
Green peas	4976	1	348	8	357	0.0	1.7	0.0	1.8
Pumpkins	28,749	53	232	49	334	1.5	6.7	1.4	9.6
Strawberry	6224	20	157	47	224	0.1	1.0	0.3	1.4
Total		8383	14,913	968	24,264	140.5	166.8	16.4	323.7

3.2. Virtual Water Estimation

The virtual water estimates varied among the three regions. The PCA found that 88.1% of the variability in the data showed a response to the grouping of regions (**Figure 4**). The LFV and VI had similar growing season lengths, and their ellipses overlap, while the OK had the driest climate among the three regions and the highest virtual water (**Figure 4**). Additionally, comparing the virtual water under different soil textures, the OK soils had virtual water up to two times higher than the LFV and VI for the same soil texture (**Figure 5**). This suggests that climate parameters such as the growing season have a higher influence than soil texture on virtual water estimations.

The OK region had higher variability in soil texture, and the coarser soils were the ones that varied the most when compared to the LFV and VI virtual water estimates (**Figure 5**). BC already faces water deficits, especially during summer, and with increasing climate variability, the OK is likely to experience more water shortages [24] [25]. Consequently, selecting finer soils, especially for growing crops with relatively high virtual water, presents a more compatible strategy for

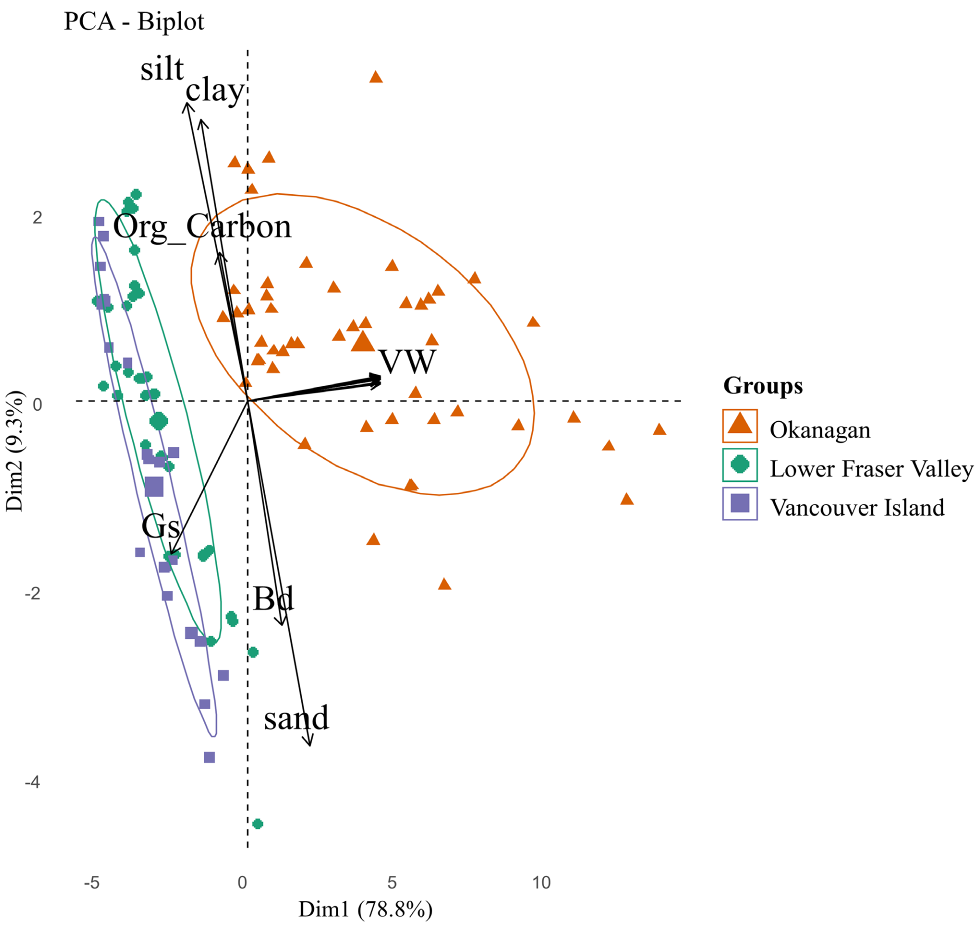

Figure 4. Principal component analysis (PCA) biplot created in R-4.1.3 with variables (Org_Carbon: organic carbon, Bd: bulk density, Gs: growing season days, sand: % Sand, clay: % Clay, silt: % Silt, and virtual water (VW) for all crops and irrigation type grouped by the three regions studied.

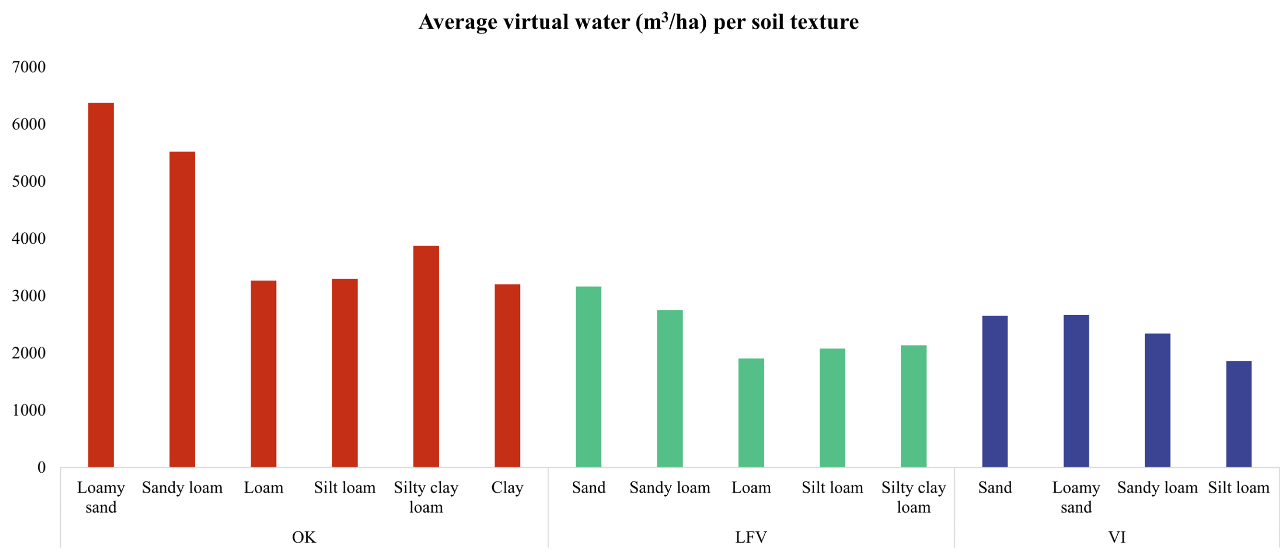

Figure 5. Mean of the virtual water (m^3/ha) for selected crops in the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI). The mean virtual water was calculated for the 9 crops studied and the soil series selected for each region, n = 18 for OK, n = 12 for LFV and n = 10 for VI. Values per region and soil texture are shown.

water scarcity scenarios in the OK region.

Sprinkler irrigation had an average annual virtual water 28% higher than drip for all crops and regions studied (**Figure 6**), which was expected as sprinkler systems lose more water due to wind and evaporation [58]. Most farms in BC currently use sprinkler irrigation, so transitioning to more efficient systems such as drip irrigation could significantly reduce local water use. This is an important opportunity, especially for drier areas such as the OK, since drip irrigation systems are suited for fruit crops and can be adapted to varied soil conditions [59] [60].

For all the crops selected, the OK had an average virtual water almost two times higher than the LFV and VI (**Figure 6**). This is consistent with the results from the PCA (**Figure 4**), with the LFV and VI showing similar groupings and the OK with a different trend. The differences in virtual water among the three regions can be explained by the hotter and drier climate in the OK. The higher evapotranspiration rates during the hot dry summer of the OK lead to higher crop water needs and higher total virtual water [21].

In the three regions studied, pumpkins and apples had the highest virtual water per hectare among the crops selected, while grapes and sweet corn had the lowest (**Figure 6**). However, the ranking of crops changed when the yield was considered (**Figure 7**). Pumpkins and apples had some of the lowest virtual water per kg of crop, while grapes and sweet corn virtual water were relatively higher (**Figure 7**). Detailed virtual water data are presented in **Table S2** and **Table S3**. The differences in virtual water in relation to yield were consistent with global assessments, with potatoes and pumpkins showing lower virtual water than berries and peas [20]. This suggests that virtual water in relation to production

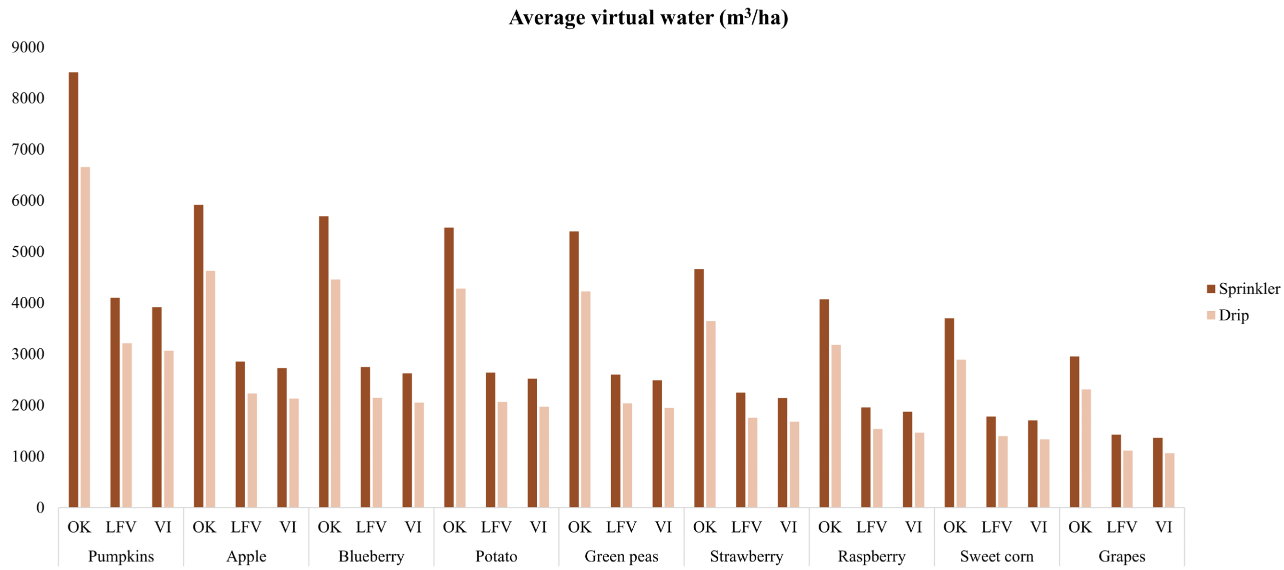

Figure 6. Mean of the virtual water (m^3/ha) for selected crops in the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI). The mean virtual water was calculated for the soil series selected for each region, n = 18 for OK, n = 12 for LFV and n = 10 for VI. Values per crop type and irrigation system, sprinkler and drip, are shown.

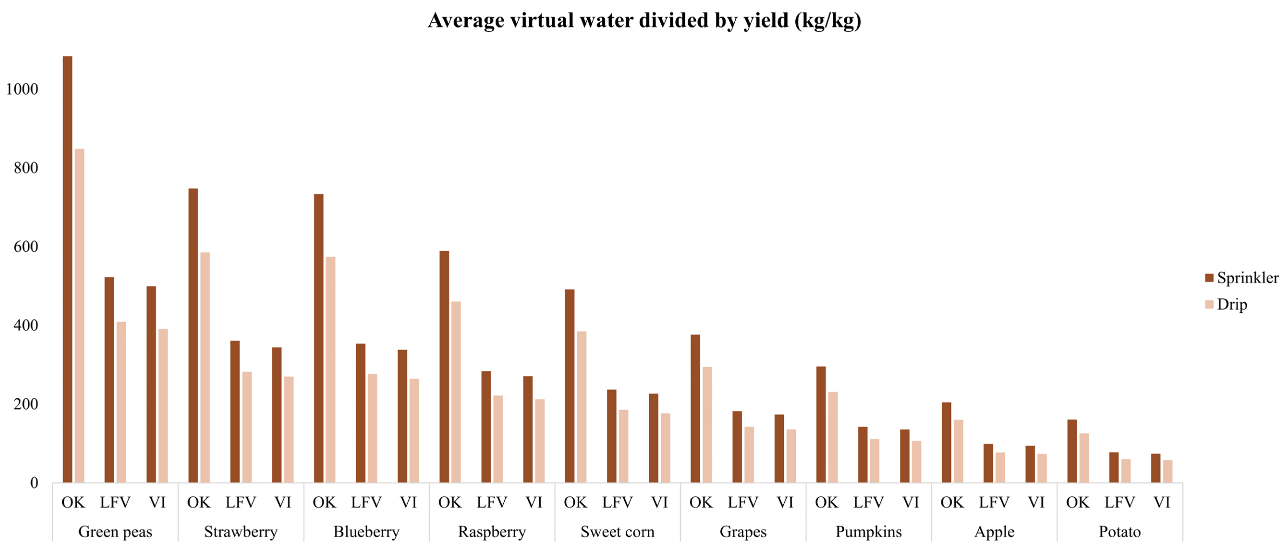

Figure 7. Mean of the virtual water divided by yield (kg/kg) for selected crops in the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI). The mean virtual water was calculated for the soil series selected for each region, n = 18 for OK, n = 12 for LFV and n = 10 for VI. Values per crop type and irrigation system, sprinkler and drip, are shown.

would be useful to consider in future studies on food loss and waste.

In the three regions, grapes had a virtual water divided by yield almost two times higher than apples (Figure 7). This can represent a potential issue for water allocation in the OK region since grape production has increased by 36% and apple production decreased by 10% from 2016 to 2021 [47] [61]. In addition, the grape virtual water was estimated without a cover crop. With cover crop, the water demand is approximately 45% higher for sprinkler systems in those regions, based on the BC Agriculture Water Calculator [46].

Blueberry showed a relatively high virtual water per hectare and per kg of crop produced (**Figure 6** and **Figure 7**). The blueberry production in the LFV increased by 16% from 2016 to 2021, while hectares of other berries dropped (for example, raspberry by 36%) [47] [61]. These changes are related to profitability but may enhance the water demand in the region in the long term [62]. Thus, measuring virtual water is a useful concept for assessing water management by comparing different land uses on a watershed or river basin scale [63].

3.3. Total Virtual Water

For the crops selected in the study, the LFV had the highest total virtual water, with 39.4 billion kg of water per year for sprinkler irrigation; the OK had the second-highest, with 35.4 billion kg of water per year for sprinkler irrigation; while the VI had a much lower total virtual water, with 2.2 billion kg of water per year for sprinkler irrigation (**Table 3**). However, the VI showed higher return per m^3 of water ($81/$m^3$) than LFV ($78/m^3) and OK ($37/$m^3$) when adding the return from the nine crops selected for the study (**Table 4**).

Comparing the LFV and OK, the OK had a lower total production (**Table 2**) and lower total sales (**Table 4**) but used relatively similar volumes of water compared to LFV to produce the nine crops selected. Blueberries and potatoes accounted for $228 million and around 34 Mm^3 of water in the LFV, whereas grapes and apples accounted for $169 million and around 33 Mm^3 of water in the OK (**Table 4**). The LFV had a total production for the crops selected 19% higher than OK (**Table 2**), but the total virtual water was only 11% higher (**Table 4**).

Table 3. Total virtual water for each crop and the three regions—Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI). Virtual water for both sprinkler (S) and drip (D) irrigation systems are shown (10^6 kg/yr).

Total virtual water (10^6 kg/yr)								
Crop	OK		LFV		VI		Total S	Total D
	S	D	S	D	S	D		
Blueberry	404	316	29,346	22,953	391	306	30,140	23,575
Apple	18,887	14,778	123	96	406	318	19,415	15,192
Grapes	13,909	10,882	321	251	243	190	14,472	11,323
Potato	1384	1083	4758	3723	469	367	6610	5172
Sweet corn	218	171	1187	928	300	234	1705	1333
Pumpkins	450	352	951	744	192	150	1593	1247
Raspberry	69	54	1458	1142	49	38	1576	1234
Green peas	5	4	905	708	20	16	930	728
Strawberry	93	73	353	276	101	79	546	428
Total	35,419	27,713	39,400	30,822	2169	1697	76,988	60,232

Table 4. Total British Columbia marketed production (ton), total farm gate (thousand $), sales rate per ton ($/ton), sales rate per kg ($/kg), total value (million $) and return per m^3 of water ($/m^3) for each crop and each region—Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI). Data obtained from Agriculture and Agri-Food Canada, 2021 [56].

Crop	2021 BC production (ton)	2021 BC farm gate (thousand $)	Sales rate per ton ($/ton)	Sales rate per kg ($/kg)	Total sales (million $)			Return per m^3 of water—sprinkler irrigation ($/m^3)		
					OK	LFV	VI	OK	LFV	VI
Apple	91,871	57395.00	624.73	0.69	63.50	0.85	2.96	3.36	6.96	7.29
Grapes	28,451	73974.00	2600.05	2.87	105.89	5.06	4.00	7.61	15.74	16.47
Blueberry	75,626	157443.00	2081.86	2.29	1.26	190.24	2.65	3.12	6.48	6.78
Strawberry	1310	6534.00	4987.79	5.50	0.68	5.37	1.61	7.34	15.23	15.95
Raspberry	3648	11763.00	3224.51	3.55	0.42	18.25	0.64	6.03	12.50	13.08
Sweet corn	7506	8921.00	1188.52	1.31	0.58	6.56	1.73	2.66	5.52	5.77
Pumpkins	7583	4551.00	600.16	0.66	1.01	4.41	0.93	2.24	4.64	4.85
Green peas	1637	2131.00	1301.77	1.43	0.01	2.48	0.06	1.32	2.74	2.87
Potato*	107,750	59373.00	551.03	0.61	5.23	37.27	3.84	3.77	7.82	8.19
				Total	$178.58	$270.50	$18.42	37.45	77.63	81.26

*Potato data obtained from Potato Market Information Review reports [64].

Consequently, the LFV had higher returns per m^3 of water than the OK (Table 4), which means that the water used in the OK brought less revenue than in the LFV for the nine crops selected.

The nine crops selected also varied in return per m^3 of water within each region. Blueberries had a lower return per m^3 of water than the other berries studied and a higher virtual water per kg of crop (Table 4). If blueberry production continues to rise in the LFV, this may represent a risk for local water allocation for this region in the longer term. As for the OK, grapes were the more economic choice than apples, with higher revenue per ton and higher return on water invested (Table 4). However, the virtual water per kg of crop for grapes is almost two-times higher than apples (Figure 7). Thus, as this industry continues to grow, the pressure on summer water withdrawals may continue to rise in the OK region.

The different crops showed different water requirements and the different irrigation systems provided varying efficiencies (Figure 7). Therefore, agricultural management practices can influence water resource availability in the long term [65]. To mitigate and also to prevent water scarcity scenarios, selecting crops better aligned with the local seasonal water availability will be important for the three regions. Lower water demand crops, such as apples and potatoes, finer soils, and more efficient irrigation systems such as drip are more congruent with water stress scenarios. To make such decisions, the BC Agriculture Water Calculator is a useful tool to help land managers and policymakers to meet local water demands.

3.4. Food Quality Indicators Estimation

Food quality indicators differed among the crops selected and are presented on a weight basis, e.g. 0.76 kg of constituent water per kg of sweet corn (**Figure 8**). Constituent water had a lower variability, ranging from 0.76 kg/kg for sweet corn to 0.92 kg/kg for pumpkins. Caloric energy had the opposite trend, with pumpkins showing the lowest content of 260 kcal/kg and sweet corn the highest with 860 kcal/kg (**Figure 8**). This was expected since crops with higher water in their composition are less calorie-dense.

Protein contents varied significantly among the crops selected, with apples showing the lowest value with only 2.6 g/kg and green peas the highest with 54.2 g/kg. Annual vegetables such as green peas, sweet corn and potatoes had higher caloric energy and protein contents than the perennial berries studied (**Figure 8**). Additionally, protein may be used as a proxy for N content based on nitrogen-to-protein conversion factors for different food types, commonly ranging from 4.4 to 6.25 [66].

Vitamin C contents were similar for apples, grapes, pumpkins and blueberries, ranging between 0.03 g/kg for grapes and 0.10 g/kg for blueberries, while raspberries and potatoes were higher with 0.26 g/kg and 0.20 g/kg, respectively. Green peas had vitamin C content almost two times higher at 0.40 g/kg, and strawberries had the highest with 0.59 g/kg. P and K contents were higher for the vegetables than for the fruits studied. Green peas had the highest P content (1.08 g/kg) and potato the highest K content (4.21 g/kg) (**Figure 8**). Local productivity, climate conditions and soil management would also likely influence the estimates of energy, constituent water and nutrients for each crop; however, additional primary nutritional data for each crop and within each region would be needed.

3.5. Total Food Wastage

Around 30% of the food production in Canada is wasted throughout the FSC [10]. Considering the nine crops selected, almost 100 million kg of food is not supporting human nutrition in the three regions studied (**Table 5**). In Canada alone, 35.54 million metric tons of food is wasted every year [28] and the retail and final consumers account for more than half of that (20% out of 30%) [10], mainly associated with improper storage, excess purchases, misunderstanding of expiration dates and high aesthetically-pleasing food expectations [67]. To address this, Canada committed to the United Nations 2030 Agenda of Sustainable Development in 2015, supporting the target to halve the global food waste per capita at the retail and final consumer levels [68].

Different compositions of each crop make their impact vary among the food quality indicators selected for the study (**Figure 9**). Due to their composition, sweet corn and green peas showed higher losses of protein and P, while strawberries had higher losses of vitamin C in the three regions. Potato accounted for a high share of the waste and loss of all the indicators in the three regions (**Figure 9**). In

Crop	Constituent water (kg/kg)	Energy (kcal/kg)	Protein (g/kg)	Vitamin C (g/kg)	P (g/kg)	K (g/kg)
Sweet corn	0.76	860	32.7	0.07	0.89	2.7
Green peas	0.79	810	54.2	0.4	1.08	2.44
Potato	0.79	770	20.2	0.2	0.57	4.21
Grapes	0.81	690	7.2	0.03	0.2	1.91
Blueberry	0.84	570	7.4	0.1	0.12	0.77
Apple	0.86	520	2.6	0.05	0.11	1.07
Raspberry	0.86	530	12	0.26	0.29	1.51
Strawberry	0.91	330	6.7	0.59	0.24	1.53
Pumpkins	0.92	260	10	0.09	0.44	3.4

Figure 8. Constituent water (kg/kg), energy content (kcal/kg), protein content (g/kg), vitamin C content (g/kg), phosphorus (P) content (g/kg) and potassium (K) content (g/kg) for selected crops [49].

Table 5. Total food wastage (10^6 kg/yr) of each crop in the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI).

Crop	Total food wastage (10^6 kg/yr)			
	OK	LFV	VI	Total
Apple	27.66	0.37	1.29	29.33
Blueberry	0.17	24.87	0.35	25.38
Potato	2.58	18.41	1.90	22.89
Grapes	11.08	0.53	0.42	12.03
Pumpkins	0.46	2.00	0.42	2.88
Sweet corn	0.13	1.50	0.40	2.03
Raspberry	0.04	1.54	0.05	1.63
Green peas	0.00	0.52	0.01	0.53
Strawberry	0.04	0.29	0.09	0.42
Total	42.16	50.03	4.93	97.12

the LFV, blueberry had the highest loss of constituent water and caloric energy, while potato had the highest total loss of protein, vitamin C, P and K. In the OK, apples had the highest loss of all indicators except for protein which had grapes as the highest. In the VI, potato had the highest total loss of all food quality indicators studied (**Figure 9**).

Total loss and waste of the crops selected in the three regions would be enough to meet the daily guidelines requirements of caloric energy of more than 60,000 adults per year [50]; the protein requirements of more than 40,000 adults per year [51]; and the vitamin C requirements of more than 300,000 adults per year [52] (**Figure 9**). The estimated total virtual water wastage (30%) in the three regions added up to 23 billion kg of water for sprinkler irrigation and 18 billion

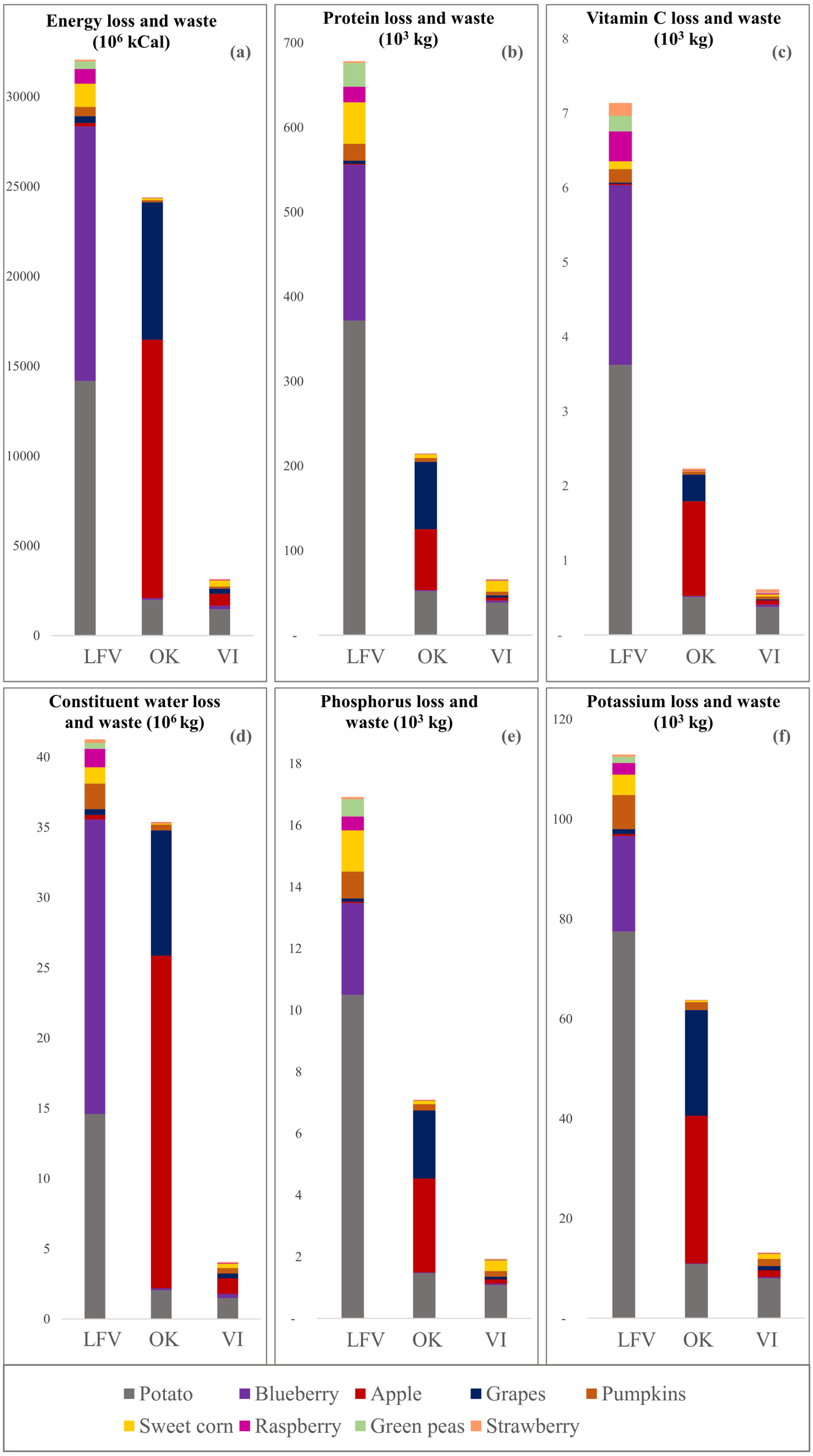

Figure 9. Caloric energy (a), protein (b), vitamin C (c), constituent water (d), phosphorus (e) and potassium (f) annual loss and waste for the crops selected in each region—Lower Fraser Valley (LFV), Okanagan (OK) and Vancouver Island (VI).

kg of water for drip (**Table 3**). This estimated virtual water loss corresponds to the annual residential water use of more than 180,000 people in BC [53]. This confirms the significance of food wastage impacts on local food security and local water demand within a regional perspective.

Macronutrients, including N, P and K, are needed by plants in relatively large quantities and are typically added annually to replace nutrients lost to crop harvest. The total P loss and waste in the three regions accounted for 26×10^3 kg, corresponding to 50 metric tons of monoammonium phosphate, while K loss and waste added to 190×10^3 kg, corresponding to 317 metric tons of potash (**Figure 9**). The P and K loss and waste would be equivalent to applying monoammonium phosphate and potash fertilizers at a rate of 2 and 13 kg/ha respectively for the total area studied. The total N may be estimated as 16% of the protein contents, accounting for 154 metric tons of N wasted [66]. This corresponds to 768 metric tons of ammonium sulfate or 334 tons of urea and would be equivalent to applying ammonium sulfate or urea fertilizers at a rate of 32 or 14 kg/ha respectively for the total area studied. The loss and waste of these nutrients have important implications for soil management and fertilizer demand since chemical fertilizers are resource-intensive to produce and are becoming limited worldwide [69] [70].

4. Conclusions

Wasted food loses valuable water resources and nutrients which can contribute to healthy human populations. Currently, additional local information is needed to evaluate the differences and magnitude of local food waste and water demand in relation to the global estimates. Besides, most available food waste reports focus on global economic estimates of individual components of energy or water or nutrient loss. This study compared three important agro-climatic zones in BC, Canada, and assessed the integrated impacts of food waste on local water resources, human nutrition and soil management.

From the virtual water estimates based on the BC Agriculture Water Calculator, climate parameters had a higher influence than soil texture on virtual water estimation in the three regions. The OK had the driest climate among the regions studied and virtual water up to two times higher than LFV and VI for the same soil texture. Thus, the local agro-climatic zone is an important consideration in assessing food waste and virtual water. In addition, results confirmed that agricultural management practices influence the local water resource availability. More efficient irrigation systems such as drip, finer soils, and crops with lower virtual water, including apples and potatoes, were found more compatible for water scarcity scenarios in the three regions.

Food wastage had different nutritional implications for each crop and region. Due to their composition, sweet corn and green peas showed higher losses of protein and P, while strawberries had higher losses of vitamin C in the three regions. Potato accounted for a high share of the waste and losses of all the food quality indicators in the three regions. The total losses for each region were based on conservative estimates and would have supplied the caloric energy and protein of over 40,000 adults and the vitamin C of over 300,000 adults for one year. Total N, P and K wastage would be equivalent to applying fertilizers in the area studied at a rate between 32 or 14 kg/ha for N, 2 kg/ha for P and 13 kg/ha for K in common fertilizers used in BC.

The framework used in the study provides an opportunity to account for food wastage impacts from both environmental and nutritional perspectives, based on regional data. More local data is needed to better estimate the food wastage percentages across the different regions and crops studied, as there are only national data available. The BC Agriculture Water Calculator is an important tool for virtual water estimation but the model does not consider water sources nor agricultural management practices' effects on water demand. Thus, future research is needed to investigate the water sources in each region to better evaluate the supplemental irrigation water needed, and to evaluate more crops and Soil Management Groups to better estimate the total losses in each region.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Supplemental Materials

Table S1. Soil Management Groups considered for each region studied—Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI).

Region	Soil Management Group
OK	Glenmore
	Guisachan
	Kelowna
	Munson
	Osoyoos
	Roy creek
	Similkameen
	Skaha
	Stemwinder
LFV	Abbotsford and Ryder
	Berry
	Fairfield
	Grevell
	Monroe
	Whatcom
VI	Beddis
	Brigantine
	Chemainus
	Dougan
	Fairbridge

Table S2. Mean of the virtual water (m^3/ha) for selected crops in the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI). The mean virtual water was calculated for the soil series selected for each region, n = 18 for OK, n = 12 for LFV and n = 10 for VI. Values per crop type and irrigation system, sprinkler (S) and drip (D), are shown.

Crop	Virtual water (m^3/ha)					
	OK		LFV		VI	
	S	D	S	D	S	D
Pumpkins	8507	6654	4102	3212	3918	3065
Apple	5915	4628	2854	2233	2727	2133
Blueberry	5695	4457	2747	2148	2624	2053
Potato	5474	4283	2640	2066	2522	1973
Green peas	5400	4225	2603	2038	2488	1947
Strawberry	4661	3646	2248	1758	2145	1682
Raspberry	4069	3183	1962	1536	1875	1468
Sweet corn	3698	2895	1783	1395	1706	1333
Grapes	2954	2311	1428	1118	1364	1067

Table S3. Mean of the virtual water divided by yield (kg/kg) for selected crops in the Okanagan (OK), Lower Fraser Valley (LFV) and Vancouver Island (VI). The mean virtual water was calculated for the soil series selected for each region, n = 18 for OK, n = 12 for LFV and n = 10 for VI. Values per crop type and irrigation system, sprinkler (S) and drip (D), are shown.

Crop	Virtual water divided by yield (kg/kg)					
	OK		LFV		VI	
	S	D	S	D	S	D
Green peas	1084	848	523	409	500	391
Strawberry	748	585	361	282	344	270
Blueberry	734	574	354	277	338	265
Raspberry	589	461	284	222	271	213
Sweet corn	492	385	237	185	227	177
Grapes	376	295	182	143	174	136
Pumpkins	296	231	143	112	136	107
Apple	205	160	99	77	94	74
Potato	161	126	78	61	74	58