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Climate Change Adaptation Strategy in the Food Industry—Insights from Product Carbon and Water Footprints

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Abstract: Climate change adds an additional layer of complexity that needs to be considered in business strategy. For firms in the food industry, many of the important climate impacts are not directly related to food processing so a value chain approach to adaptation is recommended. However, there is a general lack of operational tools to support this. In this study, carbon and water footprints were conducted at a low-precision screening level in three case studies in Australia: Smith's potato chips, OneHarvest Calypso™ mango and selected Treasury Wine Estates products. The approach was cost-effective when compared to high-definition studies intended to support environmental labels and declarations, yet provided useful identification of physical, financial, regulatory and reputational hotspots related to climate change. A combination of diagnostic footprinting, downscaled climate projection and semi-quantitative value chain analysis is proposed as a practical and relevant toolkit to inform climate adaptation strategies.

Keywords: greenhouse gas; life cycle assessment; mango; potato; value chain; wine

1. Introduction

Climate change adaptation refers to the process of adjusting to the present or future expected impacts of climate change. The goal is to mitigate or avoid harm and exploit beneficial opportunities [1]. The changing climate adds another dimension of complexity to the continually changing social, technological, economic, environmental and political landscape that businesses must navigate. For many businesses, climate change may not be regarded as an immediate pressing issue, signals relating to climate change impacts may be weak or ambiguous, and the benefits of near-term strategic action may be uncertain [2]. In other cases, climate change has already come to be perceived as a material concern demanding incremental, and even transformational, responses [3,4]. That said, for the most part, firms appear to be more adept at managing change in the political-economic-market environment than the biophysical environment [3,5].

The food industry has been identified as one of the industries where climate change adaptation is of relatively high importance [5–9]. The reasons are several-fold and include the impacts of changing temperature and rainfall patterns on upstream agricultural production—yields and quality. Also important are the impacts of climate extremes and natural disasters on supply and distribution networks which can cover long distances and involve multiple modes, especially in the case of food processors operating large regionalized facilities. Most food processors depend critically on water, either as an ingredient or as a requirement for the hygienic operation of their facilities, and water supplies have the potential to be impacted significantly by climate change in some regions. In addition, some downstream stakeholders and consumers are becoming increasingly concerned about the greenhouse gas (GHG) emissions associated with the food system [10–13] and this has the potential to influence future supply chain relationships and green market segments. These are among the reasons why climate adaptation strategies are needed in the food industry.

Climate adaptation has been addressed conceptually at the level of food systems [7]. In addition, there is an abundant research literature addressing climate adaptation at the level of agricultural industries [14]. For example, climate impacts have been assessed in rice [15], maize [16], sugar [17], coffee [18], potato [19] and wine grape production [20], to name a few. These studies have generally assessed how climate change will alter the suitability of current production regions and implications for crop yield, quality and primary industry profitability. Some studies have particularly identified water supply shortages as a constraint on industry growth under climate change [21]. The adaptation to climate change by crop variety selection and altered agronomical practices are other common themes. Elsewhere, the research literature addresses the implications of climate change in relation to food safety hazards, such as food borne parasites and microbiological contaminants [22–27]. In comparison, there is a relative paucity of studies addressing climate adaptation in the food industry from a firm or value chain perspective.

A value chain can be defined as the linked set of activities by which a product is created and marketed. The emphasis on value highlights the demand driven perspective. Value chain management starts with understanding what constitutes value to the final consumer and then seeks to coordinate the activities of the individual businesses in the chain to most efficiently create value-added product and service offerings. The underlying philosophy is that value chains, rather than individual firms, are the source of sustainable competitive advantage [28]. In the case of food products, the value chain might include agricultural input suppliers (e.g., suppliers of fertilizers, agricultural chemicals), growers, agents involved in packing, transportation and storage, food processors, wholesalers, retailers and consumers. There is the potential for climate change impacts to occur at all levels of the chain and the individual adaptive responses each have the potential to enhance or detract from the chains overall performance in terms of efficiency, continuity and ultimate product attributes [29,30]. In addition, increasing awareness about climate change in the community has the potential to alter consumer perceptions about what they value in a food product as well as what new product offerings would be attractive. On this basis, the field of sustainable supply chain management has emerged and has grown in importance over the past decade [31–33], adding to the well-established practice of supply chain risk assessment [34], although neither of these fields yet address climate adaptation in any comprehensive way [35].

One of the barriers to a value chain approach to climate change adaptation is the lack of supporting operational tools [31]. Life cycle assessment (LCA) [36,37] is widely used to assess resource use and environmental impacts along supply chains; however its technical complexity can act as an obstacle to implementation in many business contexts, the results are often influenced strongly by modelling choices and parameter settings, and the technique is rarely used in a combinative way with other analytical and decision support tools [32,38]. As such, LCA is relatively underutilized in sustainable supply chain management [31].

Related to LCA is the practice of product carbon footprinting. Unlike LCA, which seeks to provide a comprehensive evaluation of environmental performance including all significant resource use and emissions, a carbon footprint is limited in scope to GHG emissions only. The number of businesses undertaking supply chain or product carbon footprinting has expanded rapidly, supported by guidelines and standards such as those published by the British Standards Institution [39] and World Resources Institute/World Business Council for Sustainable Development [40]. Nevertheless, the main goals of carbon footprinting have been the identification of opportunities for reduction of supply chain GHG emissions (*i.e.*, mitigation) and disclosure to consumers and other stakeholders. The use of product carbon footprinting as a tool to inform value chain climate change adaptation hardly raises a mention. Carbon footprints are one member of an expanding family of simplified footprint metrics [41,42], which now also includes the water footprint [43] which is also particularly relevant to understanding climate change impacts. The purpose of this paper is to investigate, through case study methods, the practicality and relevance of footprints as operational tools to support the development of climate change adaptation strategies in the food industry.

2. Case Studies

In order to achieve a detailed contextual understanding of climate change adaptation opportunities in the food industry a case study research strategy was employed. In the selection of cases, priority was placed on including a variety of agricultural production sectors, value chain characteristics and food products. Another criterion was the presence of a chain champion, actively engaged with upstream and downstream supply chain partners and able to facilitate data collection along the chain. In addition, preference was to study chains where evidence of climate risk was already apparent and which involved premium branded products. Sustainability is reported to be a more important factor in the marketing of premium branded products than those products positioned in the market to compete more on price [44]. In all, three cases studies were selected.

2.1. Smith's Potato Chips

The Smith's Snackfood Company is a unit of PepsiCo Australia and New Zealand and thereby a part of PepsiCo Inc.—the American multinational food and beverage corporation based in Purchase, New York (PEP, NYSE). The Smith's subsidiary markets a wide range of branded salted snack foods which are prominent in the Australia market. This includes the Smith's range of potato-based chips (crisps), which are marketed on the basis of quality and relative healthfulness, being cooked in premium oils with less saturated fat. The company is also fully involved in the parent's environmental sustainability agenda. For individual manufacturing sites, this includes weekly auditing of water and energy use, benchmarking of performance against other operations globally and the setting of resource use efficiency goals.

Potato chips are manufactured year round. As such, an important factor is the co-ordination of potato cultivation, storage and supply from a variety of regions across Australia according to seasonal production patterns. This can involve long distance transportation from the many farming communities to the few large manufacturing facilities strategically located for national product distribution. The quality and freshness of potatoes are also critical factors determining the quality of the manufactured chips. The contracted potato farmers grow specific varieties developed by PepsiCo with characteristics suited to chip production and follow approved agronomic practices. The value chain is managed to minimize the time between potatoes leaving the farm and being processed as this is considered a critical quality parameter. Manufacturing is just-in-time, with national distribution through supermarkets, convenience stores and a variety of other outlets. Many households purchase potato chips weekly, or at least monthly, although there are also important seasonal spikes in demand, around holidays, celebrations and major events. In initial interviews, the company expressed awareness of the need for climate change adaptation mainly in the context of potato cultivation.

2.2. OneHarvest Calypso™ Mango

OneHarvest is a privately owned Australian business marketing premium branded tropical fruits (mangoes and avocados), packaged leafy salad vegetables (mainly spinach, rocket and lettuce) as well as prepared delicatessen salads and fresh chilled meals. The products are distributed nationally through supermarkets and greengrocers. The company's history can be traced back to the 1930s with its origins in fruit and vegetable wholesaling. However, the business has been innovative in the Australian context in its development of direct marketing channels from growers to retailers as well as the development of value-added fruit and vegetable product offerings. In 1999, the company acquired exclusive, long-term commercialization rights to a new mango variety—a hybrid of "Sensation" and "Kensington Pride" registered under Plant Variety Rights as B74®. This new variety (marketed as Calypso™) is considered outstanding in terms of appearance, consistency of quality and shelf life. Calypso™ mangoes are generally sold at a price premium and are less subject to discounting than occurs with other perishable summer fruits distributed via wholesale markets.

The value chain of Calypso™ mango differs substantially from the first case study in that it involves seasonal production of a minimally transformed fresh food product. However, the farms were similarly distributed across a wide geographical area, stretching from west to east across northern Australia in order to extend the time period over which mangoes are harvestable. Mangoes are an extremely perishable fruit that require careful post-harvest handling, including temperature and disease control, in order to achieve consistent ripening and high quality retail presentation [45]. Value can readily be lost through non-compliance to post-harvest protocols and a common practice is to place OneHarvest staff inside the contracted ripening and distribution centers to oversee quality control. When overlaps occur in the harvesting of different tropical crops (e.g., mangoes and melons) demand for local infrastructure used in the post-harvest stages (including freight) can exceed availability and create quality control dilemmas. In Australia, mangoes are often consumed as a special occasion fruit, rather than as a staple, and the quality of the fruit is important. In common with the first case study, initial interviews revealed awareness of the need for climate change adaptation mainly in the context of the farming (orchard) stage.

2.3. Treasury Wine Estates Selected Single and Multi-Regional Products

Treasury Wine Estates (TWE, ASX) is an Australian-based global wine company. The company's winemaking legacy reaches back over 170 years with Penfolds Wine established near Adelaide in South Australia in the 1840s and the Beringer Brothers Winery established in California's Napa Valley in the 1870s. Today, the company is a complex vertically integrated business with around 11,000 hectares of vineyards, numerous winemaking and bottling facilities of various scale, as well as some bulk wine transportation and warehousing assets. The company markets around 50 wine brands, many of them premium, and most with multiple labels. The portfolio of products includes single vineyard wines, others produced from grapes from a single region but multiple vineyards, and others again which are blended from grapes selected from across multiple regions in order to achieve consistent quality characteristics from one vintage to another. For this project, a selection of Australian single and multi-regional products were studied, which were considered indicative of the broader portfolio of value chains.

The value chains of Treasury Wine Estates differ considerably from the other case studies due to the multiplicity of brands and products and the complex interactions with grape quality. Grape quality is closely monitored with the view to directing premium fruit into premium product lines. Grapes are sourced from the company's vineyards as well as purchased from other growers under a variety of arrangements. The company operates large-scale high-efficiency winemaking and bottling facilities in major production regions, as well as smaller facilities associated with certain iconic labels or acquired through historic vineyard purchases. To maximize the winemaking potential of grapes they must be harvested at the optimal time. Depending on the way grapes ripen in a particular season, harvesting labor, trucking, winemaking capacity and other logistics can be stretched. In initial interviews, the company identified climate change as a factor already impacting ripening in some regions. Varieties which were traditionally harvested in sequence were beginning to overlap. Extreme weather events, with the potential to impact yields and quality, were also attributed, at least in part, to climate change. In addition, longer-term climate projections suggested that in the future certain grape growing regions may not necessarily be able to produce the same wine styles they currently do.

3. Materials and Methods

3.1. General Approach

Carbon and water footprint assessments were undertaken using LCA [36,37]. However, the goal was to provide insights relevant for the purpose of informing climate change adaptation strategy. As such, the footprint assessments were screening-level diagnostic assessments, making use of readily available data sources. The input data quality was not intended to meet the requirements necessary to support product labelling or marketing claims. Also, carbon and water footprints are of high relevance to the food industry; however, they do not constitute a comprehensive assessment of environmental performance as is the goal of a complete LCA. Data used in the assessments (such as value chain energy and water use as well as other inputs to production, *etc.*) were obtained directly from the firms involved in the case studies and their value chain partners. Measured data were used wherever possible, but in some cases estimates obtained from experts familiar with production processes were used. For farm water use, the data generally covered three consecutive years. Where data gaps occurred, various LCA inventory databases were utilized with the goal of selecting data most relevant to the specific product systems being studied. This approach was deemed consistent with the study objectives and necessary for the practical operationalization of the method.

3.2. System Description

In the case of Smith's potato chips, the unit of analysis, also known as the functional unit in LCA, was 1 kilogram of chips at the point of retail sale. Variations of flavor and package size, known from previous research to have little bearing on carbon and water footprint results (unpublished), were not differentiated. The assessment was based upon PepsiCo's facility at Tingalpa, close to Brisbane, and included all of the major upstream processes (potato production including seed pipeline and production of farming inputs such as fertilizer, the production of other food ingredients as well as packaging and transportation to Tingalpa) and downstream processes (distribution to retail outlets).

In the case of Calypso™ mango, the unit of analysis was 1 kilogram of fresh mango delivered to retail distribution centers in the major consumption hubs of Sydney (70%) and Melbourne (30%). The assessment took into account the variations in orchard inputs and yields over a 25 year orchard lifespan and the focus was the major Calypso™ production centers near Darwin and Katherine in Australia's Northern Territory. Inputs to orchard production (electricity, fuels, fertilizers, agricultural chemicals, irrigation, *etc.*) were included in the assessment, as well as all of the major downstream processes, such as harvesting, packing, cooling, transportation to ripening centers, and subsequent transportation to market.

In the case of Treasury Wine Estates, the unit of analysis was 1 liter of bottled and packaged wine delivered to Australian distribution centers. Due to the complexity of vineyards, wineries and products, a selection of product life cycles were studied from which broader implications could be extrapolated. In addition, the assessment was designed to utilize relevant LCA data already held by the firm. The carbon footprint was based on a single regional brand (multiple varieties and labels) produced in a South Australian viticultural area and bottled in the Barossa Valley. The water footprint assessment contrasted a single-region Chardonnay produced in Victoria from local grapes and a multi-region Chardonnay produced from grapes grown in five viticultural regions. In all cases, the assessment included vineyard production and associated inputs, winemaking, packaging and transport.

3.3. Carbon Footprint Assessment

Carbon footprint modelling followed PAS2050 [39], the widely adopted process LCA-based method of calculating the GHG emission of a product. Emissions from agricultural soils as a result of inorganic nitrogen fertilizer application were calculated following the method of the Australian national GHG inventory [46]. Recent land use change (deforestation) did not feature in any of the systems and possible changes in soil carbon were ignored due to a lack of relevant data. Capital items (such as farm tractors and fences, building and equipment) were also excluded from the assessment. To calculate the carbon footprint (expressed in kg CO_2e) the 100-year global warming potentials for GHGs published by the IPCC were used [47].

3.4. Water Footprint Assessment

Water footprint modelling followed the method of Ridoutt and Pfister [48] as recommended in the ENVIFOOD Protocol [49], which is the procedure for harmonized assessment of environmental performance of food and beverage products in Europe. There is no equivalent recommendation for food and beverage products in Australia. The water footprint assessment included consumptive water use only and not water pollution (*i.e.*, what is termed a water availability footprint in ISO14046 [43]). In summary, to calculate the water footprint (WF) each instance of consumptive water use (CWU) was multiplied by the relevant local water stress characterization factor and then summed across the product life cycle. The result was expressed in the units L H_2Oe, where 1 L H_2Oe represents the burden on water systems from 1 L of consumptive freshwater use at the global average water stress [50].

4. Results

For the three case study products, the life cycle (farm to retail distribution center) results for consumptive water use, water availability footprint and carbon footprint are summarized in Tables 1–3. In presenting the results, the absolute values are not reported. This is because the research method involved screening-level assessments designed to inform climate adaptation strategy. The method was not intended to produce results suitable for making accurate quantitative comparisons between products. The absolute size of the carbon and water footprint results are described in relation to the broad categories defined in Tables 4 and 5.

Table 1. Smith's potato chips: profile of life cycle consumptive water use (CWU), water availability footprint (WF), carbon footprint (CF) and hotspots for climate change adaptation [1].

Life Cycle Stage	CWU	WF	CF	Hotspots						
	%	%	%	WF	CF	Water Scarcity	Water Pricing	Energy Pricing	GHG Regulation	Data Uncertainty
Potato cultivation										
Irrigation	87	96		X		X	X			X
Fertilizer prod.	1	1	13		X					
Fertilizer use			10		X					
Fuels			13		X			X	X	
Other inputs										
Other ingredients	10	2	18		X					X
Packaging			9							
Transport to factory			7							
Smith's operations										
Electricity			13		X			X	X	
Natural gas			8		X			X	X	
Water intake	1									
Other	1	1								
Distribution			9		X			X	X	

[1] Empty cells in the environmental metrics columns refer to values less than 1%.

Table 2. OneHarvest Calypso™ mango: profile of life cycle consumptive water use (CWU), water availability footprint (WF), carbon footprint (CF) and hotspots for climate change adaptation [1].

Life Cycle Stage	CWU	WF	CF	Hotspots						
	%	%	%	WF	CF	Water Scarcity	Water Pricing	Energy Pricing	GHG Regulation	Data Uncertainty
Orchard irrigation	98	63		X		X	X			X
Orchard energy use		2	22		X			X	X	X
Orchard fertilizer.										
Production		2	7							
Emission			2							
Other inputs		12	5							
Packing & cooling		1	4							
Packaging	1	20		X						X
Ripening			4							
Distribution			55		X			X	X	

[1] Empty cells in the environmental metrics columns refer to values less than 1%.

Table 3. Treasury Wine Estates selected products: profile of life cycle consumptive water use (CWU), water availability footprint (WF), carbon footprint (CF) and hotspots for climate change adaptation [1].

Life Cycle Stage	CWU	WF	CF	Hotspots						
	%	%	%	WF	CF	Water Scarcity	Water Pricing	Energy Pricing	GHG Regulation	Data Uncertainty
Vineyard										
Irrigation	97	97		X		X	X			X
Electricity			1							
Fuels			1							
Other										
Winery										
Electricity		1	2							
Water intake	1					X				
Organic waste			3							
Other			1							
T'port to bottling			1							
Bottling										
Packaging	1	1	23		X			X	X	X
Electricity			1							
Distribution	1	1	68					X	X	

[1] Empty cells in the environmental metrics columns refer to values less than 1%.

For Smith's potato chips, the great majority (87%) of water use occurred in the irrigation of potato crops (Table 1). The production of other food ingredients (vegetable oils and flavor ingredients) required much less water (10%) and water use in other value chain stages was trivial. As a result of some potato farming regions being located in high water stress locations, the water footprint was substantially determined by potato irrigation (96%). In comparison, the profile of GHG emissions was much more evenly distributed across the value chain: potato cultivation contributed 36%, Smith's operations contributed 21%, distribution and packaging each contributed 9%. Based on the categories defined in Tables 4 and 5 the carbon and water footprints for this product would be described as Category C and Category D in comparison with other food products.

Table 4. The typical carbon footprint of a selection of common foods (at point of retail) [1].

Category	Range kg· CO_2e· kg^{-1}	Examples
A	<1	Tea, mineral water, vegetable soup, boiled potato, soda, black coffee, cooked lentil, beer, potato salad, cooked onion, fresh clementine, quiche Lorraine, fresh orange, cooked pasta, fresh apple, whole wheat bread, white sugar, cooked white rice
B	From 1 to <2	Honey, canned applesauce, sunflower oil, red wine, canned beans drained, pasteurized orange juice, walnuts, raw tomatoes, semi-skimmed milk, raw carrot, raw endive, green salad without dressing, fruit yogurt, frozen potato fries, canned ravioli, cream cheese with 20% fat, tabbouleh
C	From 2 to <5	Pain au chocolat, olive oil, scalloped potatoes, plain yogurt, banana, vegetable oil spread, crackers, sardines canned in oil, canned stew, slated potato chips, brioche, cream, smoked salmon, fried breaded fish, pie or fruit tart, pizza, boiled egg
D	From 5 to <10	Canned tuna, baked cod, poultry cutlet, roasted chicken, cooked ham, sausage, cheeseburger, cooked bacon, camembert
E	>10	Gruyere 45% fat, cooked shrimp, chopped steak with 15% fat, lamb chops, unsalted butter

[1] Adapted from Vieux *et al*. [51].

Table 5. The typical water availability footprint of a selection of common foods [1].

Category	Range L· H_2Oe· kg^{-1}	Examples
A	< 5	Fresh milk (New Zealand), whole wheat (South-eastern NSW, Australia), fresh milk (South Gippsland, Australia), white wine (Portugal), fresh tomato (Bundaberg, Australia), fresh tomato (NSW Tablelands, Australia), whole wheat (Chang basin, China)
B	From 5 to <50	Soda from Australian sugar, beef cuts (Bathurst, Australia), fresh milk (Heilongjiang, China), maize (Songliao basin, China), maize (Chang basin, China), maize (Beijing region, China), beef cuts (North coast NSW weaners, grass fattened and feedlot finished, Australia), beef cuts (inland NSW weaners, grass fattened and feedlot finished, Australia), fresh tomato (Sydney region, Australia), Peanut M&M®(Australia), lamb cuts (western Victoria, Australia), beef cuts (Scone, Australia)
C	From 50 to <500	Fresh tomato (Beijing region, China), fresh tomato (Shouguang, China), whole wheat (Murrumbidgee region, Australia), maize (Hai basin, China), beef cuts (Parkes, Australia), maize (Huai basin, China), Dolmio® pasta sauce (Australia), maize (Huang basin, China), whole wheat (Huai basin, China), whole wheat (Beijing region, China), fresh milk (California, USA)
D	>500	Beef cuts (Gundagai, Australia), whole wheat (Huang basin, China), whole wheat (Hai basin, China)

[1] Data sources: [48,52–58].

In the case of OneHarvest Calypso™ mango, consumptive water use in the value chain was also predominantly crop irrigation (98%; Table 2). However, the orchards in Australia's Northern Territory are located in regions which are currently regarded as having very low water stress. As such, orchard irrigation represented only 63% of the water footprint. The manufacturing of packaging materials (predominantly corrugated cardboard box) contributed 20% to the water footprint and the manufacturing of agricultural chemicals contributed another 14%. The carbon footprint was significantly determined by the distribution stage of the chain (55%) as the transportation distances from northern Australia to the major urban centers is enormous: 3742 km from Darwin to Melbourne via Adelaide, and 3896 km from Katherine to Sydney via Gatton. The carbon footprint was sensitive to the proportion of product shipped by rail versus road. Based on the categories defined in Tables 4 and 5 the carbon and water footprints for this product would be described as Category A and Category B in comparison with other food products.

For the selection of Treasury Wine Estates products consumptive water use occurred mainly in the vineyard (97%; Table 3) and this was the main contribution to the water footprint (also 97%). However, there were large variations in irrigation water use from year to year at some of the vineyards. In an extreme case the irrigation water demand varied several fold. For the multi-regional blended wine, the water footprint was sensitive to the proportion of grapes sourced from different vineyards as the local water stress varied from very low to extremely high. The carbon footprint was mainly determined by the distribution stage of the chain (68%), although the packaging materials (e.g., glass bottles) were also important (23%). Based on the categories defined in Tables 4 and 5 the carbon and water footprints for this product would both be described as Category D and Category C in comparison with other food products.

5. Discussion

For firms in the food industry, many of the important climate change impacts/opportunities occur in parts of the value chain which are outside their formal operational control. It is therefore an imperative that climate adaptation be approached from a value chain perspective. However, there has been identified a general lack of operational tools to support firms in taking this approach [31]. Many businesses in the food industry are becoming increasingly aware of product carbon and water footprinting and there are now a considerable number of protocols, structured programs and private sector consultants available to support their implementation. However, the focus of their use is rarely climate change adaptation despite the apparent relevance of the information obtained. The purpose of this study was to explore the use of carbon and water footprints as a diagnostic tool to assist firms in the food industry to formulate a value chain-based adaptive response to climate change.

For the three different food industry case studies, the carbon and water footprint profiles were used to identify climate adaptation hotspots in the chain (Tables 1–3). In total, seven hotspot analyses were performed, covering a variety of operational, financial, regulatory and reputational concerns:

1. Water footprint reduction: Under climate change there may be heightened societal concern about water scarcity and increasing reputational and/or market access risks/opportunities associated with water footprint labelling [59].
2. Carbon footprint reduction: As with the previous issue, climate change may lead to heightened societal concern about the GHG emissions associated with products and therefore increasing reputational and/or market access risks/opportunities associated with carbon footprint labelling [59].
3. Water scarcity: Water scarcity is a concern in many parts of the world and this has the potential to be exacerbated under climate change. Water scarcity represents a physical risk to irrigation dependent agricultural production systems as well as the operation of food processing facilities. Under extreme circumstances, water scarcity has the potential to completely disrupt value chains [60].
4. Water pricing: Water scarcity also has the potential to lead to increased water pricing, which is a financial risk, especially to operations which use large water volumes [60].
5. Energy pricing: In addition to water pricing, climate change has the potential to impact energy prices as businesses in the energy sector respond to government policies and seek to constrain high emission sources of energy, and commercialize new energy technologies [60].
6. GHG regulation: GHG regulations, such as carbon taxes and emissions trading schemes, represent a further climate change related financial risk.
7. Data uncertainty: LCA is an iterative process. To be cost effective, a screening analysis is usually first undertaken, which identifies critical elements in the value chain which can then be studied in more detail. As a final hotspot analysis, parts of the value chain with significant data uncertainty were identified [61].

5.1. Smith's Potato Chips

For Smith's potato chips the water footprint was categorized as Category D (>500 L· H_2Oe· kg^{-1}; Table 5). The hotspot for water footprint reduction was irrigation water used for potato cultivation (Table 1). In comparison, other water use in the value chain, including at Smith's operations, was relatively minor. Considering that the potatoes used in Smith's chips are custom grown and not sourced from a commodity market, this value chain activity is highlighted as a major focus for climate adaptation strategy, and this is already recognized by Smith's and demonstrated in the company's Sustainable Farming Initiative. In addition, irrigation of potatoes involves large water volumes (meaning any change to water pricing could be a financial concern), some of the irrigation is in high water stress locations (meaning a threat to supply continuity if water supplies for irrigation became limited), and there was data uncertainty regarding the extent that climate change might alter future irrigation water requirements. The carbon footprint was assessed as Category C (2–5 kg· CO_2e· kg^{-1}; Table 4), with potato cultivation and supply again the value chain activity making the largest proportional contribution. This further reinforces the importance of the company's Sustainable Farming Initiative. A data uncertainty hotspot was the GHG emissions of cooking oils, which are sourced from different suppliers from commodity markets. Only about 10% of GHG emissions were related to emissions from fertilizer applications. As such, the major risks related to energy pricing and GHG regulation were in relation to electricity and fuels. Although not presented here, the carbon and water footprint data enables the impact of water and energy pricing scenarios to be modelled.

5.2. OneHarvest Calypso™ Mango

For OneHarvest Calypso™ mango the water footprint was categorized as Category B (5–50 L H_2Oe· kg^{-1}; Table 5) and the carbon footprint as Category A (<1 kg· CO_2e· kg^{-1}; Table 4). As such, potential rising interest by consumers and retailers in environmental footprint metrics probably presents a lesser risk for this product than the case study above. As a general rule, there is less concern in the sustainable diets community about the environmental burdens of fruits and vegetables [62,63]. However, mango orchards do require large volumes of water for irrigation (Table 2). At the present time, the orchards producing Calypso™ mango in the Northern Territory are in areas regarded as low water stress. A critical uncertainty is the ability of local aquifers to meet increasing demand for water in the region and the potential future change in aquifer recharge under climate change, affecting water scarcity and water pricing. As such, water for irrigation is deemed to be a hotspot for climate change adaptation in this value chain. The major contribution to the carbon footprint was fuel used in transporting mangoes from farm to retail distribution centers. Changes in fuel pricing as a result of GHG regulations could represent a significant financial risk. As such, the distribution network is considered another major hotspot for climate change adaptation.

5.3. Treasury Wine Estates Selected Single and Multi-Regional Products

For the selected Treasury Wine Estates products the carbon and water footprints were classified as Category D and C in comparison to a broad range of food products (5–10 kg· CO_2e· kg^{-1} and 50–500 L· H_2Oe· kg^{-1}; Tables 4 and 5). The carbon footprint of wine has been frequently studied and found to average around 1.9 kg· CO_2e· L^{-1} ([64]; considering the vineyard to retail distribution stages only), which would be classified as just within Category B according to Table 4. Although the various wine carbon footprint studies are not directly comparable, there is an indication that the selected Treasury Wine Estates products are above this average and this could present a hotspot for climate change adaptation. Although wine consumers appear to show little understanding of carbon footprints at present [65], there is the possibility that carbon footprints may become more influential in future. The production of packaging materials (especially glass bottles) and distribution were the parts of the supply chain accounting for the majority of the carbon footprint and also the stages most sensitive to energy pricing and GHG regulation (Table 3). The water footprint, being within Category C, is also of concern from the perspectives of reliable water availability, water pricing and water footprint reduction. The vineyard is therefore another hotspot as the majority of water use occurs here and it was observed that water demands varied greatly from one vineyard to another and from one year to the next in order to achieve yield and quality targets. There is therefore also some data uncertainty about the future irrigation water demands under climate change. Access to reliable water supplies is especially relevant in the case of perennial crops where there is not the opportunity as exists in annual cropping to vary what is planted according to water availability. It was apparent that products originating from single vineyards and single regions were generally more vulnerable to climate change than products blended from grapes from multiple regions as there was scope to modify the regions from which grapes were sourced. This could be from year to year or through a long term strategy of transitioning grape production away from areas where water supply is most vulnerable. This is in addition to the many mitigation strategies already being employed at individual vineyards which include increasing access to reliable water through participation in water trading schemes, lining dams, recycling water, and using composts and mulches.

6. Conclusions

When the three food industry case studies were considered together, it was evident that most of the climate adaptation risks and opportunities were either upstream or downstream of food processing, underscoring the importance that firms in this sector adopt a value chain approach to forming adaptation strategies. The problem is the lack of a structured method that is both practical and operational. In this study, carbon and water footprints were conducted at a low-precision screening level. The approach was highly cost-effective compared to high definition footprint studies which have high data quality requirements and which are intended to support environmental labels and declarations. In summary, it was found that these screening level carbon and water footprints provided a useful basis for mapping value chains and identifying hotspots of physical, financial, regulatory and reputational risk associated with climate change. Overall, we considered this to be a valuable starting point to inform climate adaptation strategies. Limitations of the approach were also evident. Direct implications of temperature and precipitation changes on crop production and value chain operations were not assessed. Possible climate change impacts on product quality were also not evaluated. Thirdly, the footprinting approach did not delve into consumer attitudes which could be relevant in understanding product opportunities and market segmentation opportunities related to climate change. All this points to the conclusion that a combinative approach is ultimately needed which integrates carbon and water footprints with downscaled climate projections and other semi-quantitative value chain analysis tools in a multi-dimensional assessment.

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