












## Article

# Causal Relations of Upscaled Urban Aquaponics and the Food-Water-Energy Nexus—A Berlin Case Study

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**Abstract:** Aquaponics, the water-reusing production of fish and crops, is taken as an example to investigate the consequences of upscaling a nature-based solution in a circular city. We developed an upscaled-aquaponic scenario for the German metropolis of Berlin, analysed the impacts, and studied the system dynamics. To meet the annual fish, tomato, and lettuce demand of Berlin's 3.77 million residents would require approximately 370 aquaponic facilities covering a total area of 224 hectares and the use of different combinations of fish and crops: catfish/tomato (56%), catfish/lettuce (13%), and tilapia/tomato (31%). As a predominant effect, in terms of water, aquaponic production would save about 2.0 million m<sup>3</sup> of water compared to the baseline. On the supply-side, we identified significant causal link chains concerning the Food-Water-Energy nexus at the aquaponic facility level as well as causal relations of a production relocation to Berlin. On the demand-side, a 'freshwater pescatarian diet' is discussed. The new and comprehensive findings at different system levels require further investigations on this topic. Upscaled aquaponics can produce a relevant contribution to Berlin's sustainability and to implement it, research is needed to find suitable sites for local aquaponics in Berlin, possibly inside buildings, on urban roofscape, or in peri-urban areas.

**Keywords:** water; circular city; causal loop diagram CLD; nature-based solutions NBS; water scarcity; dietary shifts; aquaponic farming; fish/plant harvest ratio

## 1. Introduction

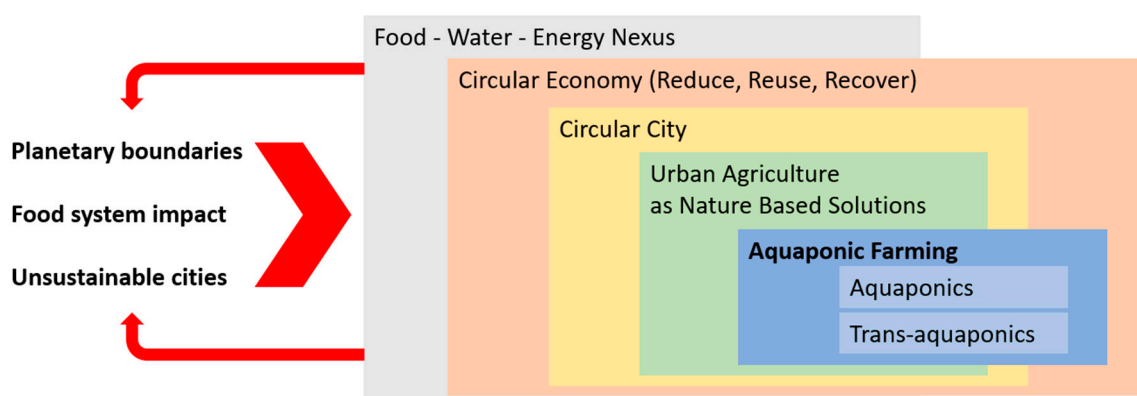
Human activities cause significant damage to nature and the consequences are already apparent in 'human suffering', towering economic losses, and the accelerating erosion of life on Earth [1]. In order to address the most pressing global issues, the UN formulated 17 sustainable development goals (SDGs) [2], but increased efforts are needed to achieve

these SDGs, as is evidenced by the current compliance review [3]. Therefore, a ‘Decade of Action’ has been declared to fulfil the 2030 Agenda [4]. The German Federal Government has taken up this UN demand by revising its sustainability strategy, which now contains six transformation areas including ‘circular economy’ and ‘sustainable agricultural and food systems’ [5]. The food sector, which addresses both transformation areas, is the most tremendous burden on the Earth’s ecosystems [6] and a major contributor to the transgression of the nine planetary boundaries identified by Rockström et al. [7]. If crossed, these boundaries could potentially endanger human existence [8].

Fisheries have already reached their limits [9] and the increase in fish consumption over the past four decades is mainly covered by aquaculture, which is the world’s fastest-growing food production industry [10]. This growth involves environmental problems and animal welfare risks [11]. In 2000, a study concluded that aquaculture needs to reduce wild fish inputs into feed [12]. A retrospective review 20 years later found that overall sustainability increased but dependence on marine ingredients continued [13]. Marine aquaculture raises environmental issues [14,15], e.g., the negative landward flux of the essential mineral phosphorus [16]. The alternative to marine aquaculture is freshwater aquaculture; however, freshwater aquaculture generates wastewater, especially in flow-through systems [17], and it is estimated that over 80% of global wastewater is not adequately treated [18]. Increased water use efficiency decouples economic growth from water use, e.g., by using less water in agriculture through the introduction of new technologies [19]. One water-efficient technology that reduces wastewater is aquaponics (AP), the coupled production of fish and crops [20,21]. Additionally, AP decreases fertiliser use and greenhouse gas emissions associated with its food production [22].

Cities are critical to the success of sustainable development [23]; thus, initiatives and proposals set out at global, European, and municipal levels to promote the transformative power of cities are aimed at the common good—e.g., the World Cities report [24], the New Leipzig Charter [25,26], or the roadmap to Amsterdam Circular [27]. The circular city (CC) is designed as a regenerative and restorative urban living system [28] by reducing, reusing, and recovering [29]. Nature is part of the transformation [30]: nature-based solutions (NBS) [31] can support closing the adaption gap [32] and the coupling of NBS units form a significant part of circularity in cities [33,34]. Urban agriculture, which is attracting increasing attention [35], contributes towards circular cities [36]. Strengthening urban and peri-urban food production, integrating it into city resilience plans, and applying an ecosystem approach that guides holistic land use planning and management are recommended approaches by the Milan Urban Food Policy Pact [37].

There is a need for upscaling NBS and, inter alia, the promotion of sustainable agriculture and food systems is suggested by the UN [38]. Aquaponic farming, which comprises AP and trans-aquaponics [39], is considered an NBS unit [40] and should be addressed as well in tackling the issue of whether and under what conditions it makes sense to scale up urban aquaponics. In order to understand its system dynamics, it is necessary to investigate the dependencies and causal relationships of variables by systems analysis. We use a comparative life cycle assessment on the impact of aquaponics on the local urban environment [41] and compare environmental footprints of different scenarios with a secondary analysis. Impact evaluation is supported by the concept of the Food-Water-Energy (FWE) nexus, which describes the interlinkages between these three sectors and can be applied to an urban context [42]. The relations between different methodological approaches related to this study are shown in Figure 1.



**Figure 1.** Different methodological approaches that can be applied to solve global problems; boxes indicate set relations.

The German metropolis Berlin (DE), similar to many other cities, has signed the Milan Urban Food Policy Pact [37] and committed to establish fair and sustainable food systems. In order to know whether upscaled urban aquaponics can contribute to this objective, we use Berlin as a case study and intend to pursue the following goals: (1) supply-side changes—to develop a scenario for meeting the demand for fish, tomato, and lettuce through upscaled urban aquaponics in Berlin; (2) to describe the environmental impacts of the scenario; (3) to investigate causal links between aquaponic variables and the FWE nexus sectors; (4) to analyse the supply-side causal relations of a production shift to Berlin; and (5) demand-side changes—to discuss the impact due to dietary shifts, e.g., pescatarian diet. Economic, social, and urban development implications are beyond the scope of this study but are considered prospective research.

## 2. Materials and Methods

### 2.1. System Analyses Considering Urban Food-Water-Energy Nexus

The Food-Water-Energy Nexus (FWE nexus) is a recent paradigm that is rapidly expanding in terms of policy documents and academic literature [43,44] and has also expanded to other sectors such as land use or climate [45]. In general, the nexus provides a system-based perspective and refers to the interactions between parts of a system or systems [42]. Although the FWE nexus has been criticised for masking power relations and social inequalities [46], its importance as an integrated approach is widely acknowledged [42]. In order to explore the relationships of variables involved, a system dynamics approach utilising causal loop diagrams can be used, e.g., for constructing a FWE nexus model of China [47]. Many observers stress the role of cities as crucial junctures in the FWE nexus and for advancing sustainable development [48,49]. Due to its origin, the nexus represents a hybrid concept with scientific and non-scientific contributors and offers three fields of application: (1) analytical approach [50,51], (2) boundary concept [46], and (3) governance approach [48,52].

The urban FWE nexus describes interlinkages and interdependencies between the food, water, and energy sectors with their substantial impacts on climate, environment, and land use in an urban context [42,53]. In the last decade, the urban nexus has gained more attention in research and practice, with a focus on urban metabolism [54], tools, and methods for nexus assessment [51,55] as well as urban governance [48]. Nonetheless, urban spaces face some specific features such as population concentration, critical infrastructure, high resource consumption, and negative environmental impacts in small areas. These features provide obstacles but also opportunities for sustainable urban development [48,56]. This applies in particular to the food system, where the places of production and consumption have become increasingly disconnected due to the processes of industrialisation and globalisation in the agri-food sector [57]. The opportunities of the urban space arise from urban planning and more integrated sector management at the regional scale and their potential to reduce the environmental impact per capita, create synergistic improvements in

the urban system, and reconnect cities with their rural hinterlands [56]. Furthermore, cities have been considered as innovation hubs where new technologies and ideas have emerged and where localised nexus thinking and governance can be tested and implemented [48,58].

The entrance point to the FWE nexus needs to be made explicit since it determines the perspective on, e.g., infrastructure [50,53]. For this study, we have chosen a food-centric approach. We have performed two system analyses on the AP facility level and city level to investigate the causal links of the most relevant system variables.

## 2.2. Secondary Analysis of a Comparative Life Cycle Assessment

Aquaponics is the coupling of recirculating aquaculture systems (RAS) and hydroponics (HP) and a key feature is the dual use of water, which was first used to raise the fish and then to fertigate the plants [21,39]. A recent life cycle assessment (LCA) compared AP crop production with an available market mix in the Berlin metropolitan area consisting of imported and locally produced lettuce and tomatoes (Mix-DE) [41] referred to in this study as comparative-LCA. The packed and market available products originated from various countries and the respective transports to Berlin and storage were included. For the comparative-LCA, a simulation of an on-demand coupled AP [39] with a greenhouse size of 5000 m<sup>2</sup>, variable RAS size, and year-round production was used. The comparative-LCA scenario DAPS-R+ is characterised by rooftop aquaponics (here referred to as rooftop-AP) and active waste heat recovery [59] from the building below; an example of an existing rooftop AP is the Abattoir farm at the Anderlecht district of Brussels [60,61].

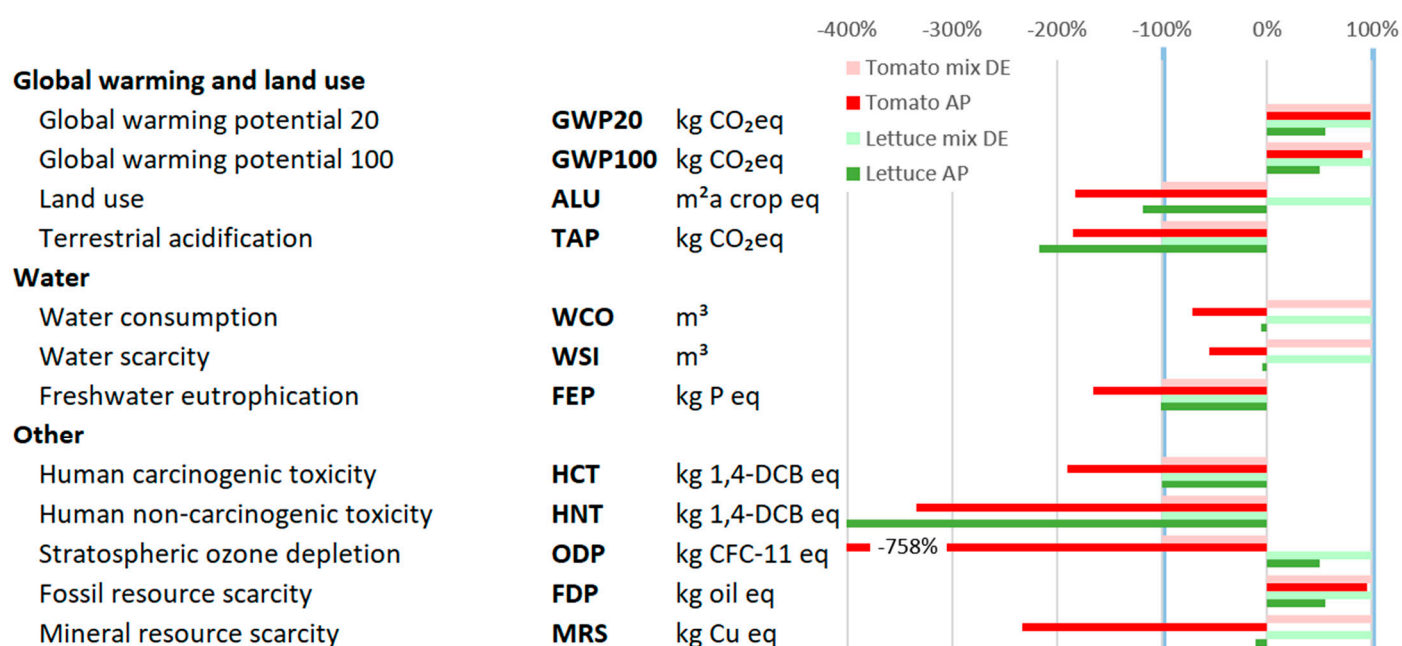
The comparative-LCA used system expansion [61,62], i.e., when allocating the environmental impacts in complex systems between products and co-product, the first option is to avoid allocation by subdividing or to expand the systems investigated [62,63]. In total, 12 environmental impact categories were selected and calculated by the comparative-LCA and further processed in the present study. Each impact category denotes an indicator that concentrates the specific environmental effects, e.g., the widely used term CO<sub>2</sub>-footprint is summarised in the indicator CO<sub>2</sub>-equivalents (CO<sub>2</sub> eq.), which is translated into global warming potential (GWP). Higher water consumption per unit produced in Southern Europe results in higher impacts of water consumption (WCO) and water scarcity (WSI) in benchmark products. While fresh water is used for irrigation in regular HP, in a perfectly balanced on-demand coupled system, all water consumed in the HP consists nutrient water from the RAS subsystem. Thus, there is no fresh water consumption in the HP sub-system in the simulated AP system [59,63].

Due to system expansion used in the comparative-LCA, negative values for WCO and WSI could be achieved: In the case of tomato, green waste was used for biogas and further production of heat and power and the environmental impact, according to system expansion, is allocated to the process as negative values, i.e., withdrawn. Depending on which energy source is replaced, negative values also resulted in the impact categories involved.

As the basis for a secondary analysis, we have taken data from the comparative-LCA, grouped the LCA impact categories (cf. Table 1), set the scenario Mix-DE values to +/−100% concerning tomato respectively lettuce, and calculated the relative change of the related rooftop-AP impact category. Thus, four values are assigned to each impact category, which allows a direct comparison of the environmental impacts of both scenarios. In order to visualise these relative changes of the environmental footprint, we developed a diagram comprising all 12 impact categories and their four values (cf. Figure 2).

**Table 1.** Grouped LCA impact categories; author's work based on comparative-LCA [41].

	Abbr.	Unit
<b>Global warming and land use</b>		
Global warming potential 20	GWP20	kg CO <sub>2</sub> eq
Global warming potential 100	GWP100	kg CO <sub>2</sub> eq
Land use	ALU	m <sup>2</sup> a crop eq
Terrestrial acidification	TAP	kg CO <sub>2</sub> eq
<b>Water</b>		
Water consumption	WCO	m <sup>3</sup>
Water scarcity	WSI	m <sup>3</sup>
Freshwater eutrophication	FEP	kg P eq
<b>Other</b>		
Human carcinogenic toxicity	HCT	kg 1,4-DCB eq
Human non-carcinogenic toxicity	HNT	kg 1,4-DCB eq
Stratospheric ozone depletion	ODP	kg CFC-11 eq
Fossil resource scarcity	FDP	kg oil eq
Mineral resource scarcity	MRS	kg Cu eq

**Figure 2.** Relative change in LCA impact categories for optimised rooftop-aquaponics (AP) compared to the German market mix for fresh tomatoes and lettuce (mix DE) as +/− 100%; authors work and the calculation based on data from comparative-LCA [41].

Furthermore, the absolute changes of selected impact categories were extrapolated to city-scale in order to calculate the upscaled impact reduction in the production of fresh tomato and lettuce on three LCA impact categories comparing the optimised aquaponics (rooftop-AP) with the German market mix for fresh tomatoes and lettuce (Mix-DE).

### 2.3. Upscaling Aquaponics Scenario Berlin

The UN Food and Agriculture Organization estimates 'that the world will need to produce about 50% more food by 2050 to feed the growing world population, assuming no changes occur in food loss and waste' [64,65]. Regarding the European food system, an international consortium has requested its sustainability to be of high priority for policymakers at the EU, national, and municipal level [66]. One method to meet this



request is to use sustainable production technology. Therefore, we developed a scenario in which the whole demand for tomatoes, lettuce, and fish in Berlin is hypothetically met by AP systems. The comparative-LCA study modelled an on-demand coupled AP with year-round production and a greenhouse net area of 5000 m<sup>2</sup>. In order to obtain an indication of site requirements, we estimated the aquaculture net area from 500 m<sup>2</sup> (lettuce) to 700 m<sup>2</sup> (tomato), increased the net area sum of both units by 2% (construction footprint), and rounded the gross area for the entire facility to 6000 m<sup>2</sup>. We selected two aquaponically relevant species for fish production: Nile Tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*). The production parameters for tilapia were used according to the AP system modelled by Körner et al. [41] for comparative-LCA, whereas the parameters for catfish were taken from a model case based on real production data developed by Baganz, et al. [67] and extrapolated to year-round production. Farmed fish species determine many parameters of the RAS, including the stocking density, which in turn significantly determines the amount of nutrients contained in the nutrient water transferred from the aquaculture to the hydroponic unit. In addition, the tomato has a considerably higher nutrient requirement than the lettuce. A metric which reflects these different demands as well as the coupling degree of AP units is the fish/plant harvest ratio (F/P ratio). This ratio is based on the fresh harvest weight of the entire fish and crop, excluding plant leftovers. It is a key parameter for dimensioning an AP and it can be very different.

One design goal for the upscaled AP scenario was to enforce the aquaponic principle [39] for the total demand identified in the Berlin case study conducted here. In order to achieve this goal, fish production was balanced with vegetable production across all professional AP facilities so that there was no excess production or unnecessary effluent on either side. Considering these conditions, we developed an upscaled-AP scenario with four different combinations of fish (catfish and tilapia) and plants (tomato and lettuce) with various F/P ratios: AP1 catfish/tomato (3.3), AP2 catfish/lettuce (10.2), AP3 tilapia/tomato (11.1), and AP4 tilapia/lettuce (56.2). Catfish can be farmed at much higher stocking density than tilapia. The maximum stocking density was 300 kg/m<sup>3</sup> for catfish [67] and 80 kg/m<sup>3</sup> for tilapia [59,63], which is reflected by the F/P ratios. In order to prevent a mere catfish upscaled AP scenario, we targeted a minimum share of 30% tilapia. The proportion of the AP setups in the upscaled-AP scenario was then calculated based on freshwater fish requirements to meet the irrigation demands of both vegetables by considering their respective F/P ratio.

### 3. Results

#### 3.1. Berlin: Balancing Demand and Yield

German per capita (PC) consumption of fresh and processed tomatoes was 27.2 kg in 2018/19, with processed tomatoes converted to fresh weight [68]. Regarding the import and domestic harvest of fresh tomatoes, we concluded that fresh tomatoes had a share of 9.3 kg/PC and processed tomatoes 17.9 kg/PC in 2019 based on data from BLE [69]. For freshwater fish, the shares were 3 kg/PC and 0.9 kg/PC for freshwater fish products [70]. These data were not available for Berlin and so we assumed a similar consumption pattern to estimate the demand of metropolitan Berlin by adding the non-marketable portion, e.g., waste from fish processing. With a population of about 3.77 million in 2020 [71], approximately 21 kilotonnes (kt) of freshwater fish and fish products, 108 kt of fresh tomatoes and tomato products, and 27 kt of lettuce are required per year (cf. Table 2).

**Table 2.** Annual metropolitan Berlin demand for freshwater fish/fish products, tomatoes/tomato products (converted to fresh weight), and lettuce.

Demand	Residents Berlin 2020:			3,769,962		
	Fresh/Fillet	Products	Total	Netto	Not	Brutto
	(kg/PC)	(kg/PC)	(kg/PC)	(t)	Marketable	(t)
Freshwater fish	3.0	0.9	3.9	14,703	40%	20,584
Tomato	9.3	17.9	27.2	102,543	5%	107,670
Lettuce	6.8		6.8	25,636	5%	26,918
<i>fresh tomato only</i>				35,061	5%	36,814

The following proportions of AP setups have been calculated: catfish/tomato at 56%, catfish/lettuce at 13%, tilapia/tomato at 31%, and tilapia/lettuce at 0% (cf. Table 3). Berlin's F/P demand ratio was around 6.5, while the F/P ratio of AP setup AP4 (tilapia/lettuce) was 56.2; therefore, its proportion was set to zero (cf. Table 4).

**Table 3.** Upscaled-AP scenario: Four aquaponic setups as combinations of catfish/tilapia and tomato/lettuce and their respective share to meet the freshwater fish demand of Berlin.

Fish Demand Coverage	Aquaponic Setups (AP 1 . . . AP 4)			
	Tomato		Lettuce	
Catfish	AP 1	56%	AP 2	13%
Tilapia	AP 3	31%	AP 4	0%

**Table 4.** Upscaled-AP scenario: The proposed annual yield of catfish, tilapia, tomato, and lettuce per aquaponic setup; Number of AP facilities required to achieve this yield.

Yield	Fish Yield (t)			Plant Yield (t)		AP Facilities	
Aquaponic setup	Catfish	Tilapia	F/P*	Tomato	Lettuce		
AP 1	11,527		3.3	37,508			118
AP 2	2676		10.2		27,381		27
AP 3		6381	11.1	70,912			223
AP 4 **		0	56.2		0		0
Total yield	14,203	6381	yield	108,420	27,381	required	368
fish yield share	69%	31%	demand delta	107,670	26,918		
				750	464		
fish demand	20,584						
fish yield	20,584						
delta	0						

\*) fish/plant harvest ratio  
 \*\*) AP 4 excluded because of the F/P ratio

### 3.2. Supply-Side: Impact on Berlin FWE Nexus

**Food.** The yield shares (fish/crop) of each AP setup within the upscaled-AP scenario to cover the city's demand are as follows: AP1 with 11.5 kt catfish and 37.5 kt tomato, AP2 with 2.7 kt catfish and 27.3 kt lettuce, and AP3 with 6.3 kt tilapia and 70.9 kt tomato (cf. Table 4).

In order to produce a yield of 20.6 kt fish and 108.4 kt crop (tomato and lettuce) per annum, approximately 370 AP facilities are needed and this requires a total area of 224 hectares (cf. Table 4). Fish feed and fertiliser should ideally be matched to the specific AP setup. The three AP configurations should be standardised to obtain the appropriate quantities of optimised fish feed and fertiliser needed to achieve economies of scales for the upscaling-AP scenario.

**Water.** In the present study, we extrapolated the so-called water footprint, i.e., the LCA impact category water consumption (WCO in Table 5) from the package level to the city scale. Compared to the WCO of the German market mix for fresh tomatoes and lettuce, the aquaponic production of both fresh vegetables for Berlin would save about 2.0 million cubic metres of water.

**Table 5.** Upscaled-AP scenario: Reduced impact of fresh tomato and lettuce production on three LCA impact categories; author's work and the calculation based on data from comparative-LCA [41].

LCA Impact Category	Abbr.	Unit	Tomato, Fresh		mio. packs	73.6	Lettuce		mio. packs	179.5	Total Reduction	
			Mix-DE	Rooftop AP			Mix-DE	Rooftop AP				
Global warming potential 100	GWP100	kg CO <sub>2</sub> eq	0.5760	0.5261	0.0500	3679662	0.0769	0.0385	0.0383	2822799	6502	t
Water consumption	WCO	m <sup>3</sup>	0.0142	−0.0101	0.0243	1786533	0.0033	−0.0002	0.0035	261272	2,047,805	m <sup>3</sup>
Water scarcity	WSI	m <sup>3</sup>	0.0109	−0.0059	0.0168	1237314	0.0021	−0.0001	0.0022	163054	1,400,368	m <sup>3</sup>

Regarding the LCA impact category water scarcity (WSI), about 1.4 million cubic metres of water would be saved, especially in the Almeria region of Spain where the rapid development of greenhouse horticulture has dramatically affected the availability of groundwater resources [72].

**Energy.** Replacing the German market mix of tomato or lettuce (Mix-DE) with an optimised aquaponic scenario (rooftop-APDAPS-R+) would reduce the long-term CO<sub>2</sub> footprint (GWP100 in Table 5) by 7691 t CO<sub>2</sub>-equivalents. This result can be significantly improved by using aquaponics-integrated microgrids (so-called smarthoods) where all FWE flows are circularly connected [73].

Based on data from the comparative-LCA, the relative change in environmental impact between the scenarios Mix-DE and rooftop-AP shows a reduction in the environmental footprint for all 12 LCA impact categories (cf. Figure 2).

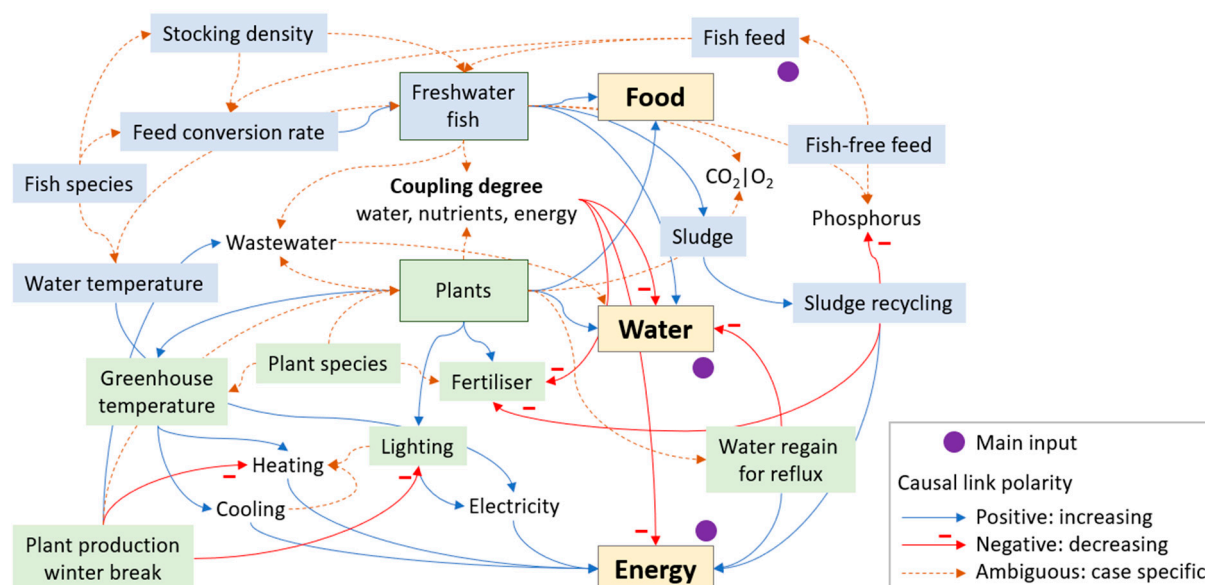
Of the 12 LCA impact categories, the FWE sector energy is represented by the impact categories GWP20 and GWP100, while the impact categories water consumption (WCO), water scarcity (WSP), and freshwater eutrophication (FEP) represent the sector water. The long-term CO<sub>2</sub> footprint (GWP100) is reduced by 9% for tomatoes and 50% for lettuce. For water consumption, the reduction is even more significant and becomes negative in the analysis of the comparative-LCA (cf. Figure 2).

### 3.3. Causalities: Aquaponic Variables and Production-Location Shift

Upscaling urban AP triggers two FWE interactions simultaneously: (1) local food production is increased and thus (2) the relocation of production occurs. Both processes result in interactions within the FWE nexus and the associated effects become relevant for the system as a whole. Thus, all causal dependencies take effect: on the local level, since AP internals and location issues gain importance due to local resource demand; and on the global level, since upscaling the shift in production-location impacts all sectors of the FWE nexus.

In order to understand the impact of AP on the three sectors of the FWE nexus, we identified significant AP variables and examined their causal relationships (cf. Table A1), which are often mediated by other variables and results in causal chains (cf. Figure 3). However, neither the complete functional scheme of an AP nor processes outside the AP system boundary (except for phosphorus) are considered when examining these AP-internal causal chains. For example, the AP nutrient coupling degree reduces fertiliser consumption, but the environmental impacts of the production and transport of the fertiliser are not considered in the causalities unlike in the comparative-LCA.





**Figure 3.** Impact of causal chains—formed by significant aquaponic variables—on FWE-Nexus (no flow chart; no functional scheme of an AP); the variables are explained in Table A1.

The variables listed in Table A1 influence the three sectors of the FWE nexus directly or via causal chains. These are the variables through which the designer/operator of an AP can influence the environmental impacts. General factors for increasing energy efficiencies such as solar panels, low-energy greenhouses, or energy-efficient pumps are not included in the scope of this consideration but must be taken into account as part of an overall concept. Ideally, this concept then considers future GHG attributions next to the current ones. Future GHG emission changes are expected to result from the process of decarbonisation, such as a changed electricity mix or biogas-fuelled combined heat and power unit (CHP). Figure 3 is a graphical representation of the causal chains formed by the AP variables.

The connectors in Figure 3 are causal links, but can easily be confused with flows. For example, the variable ‘plants’ affects the variable ‘water’ in that water demand increases with the number of ‘plants’, but the water needed flows from RAS to HP. We adopted the syntax of causal loop diagrams and extended it by adding case-specific considerations (ambiguous) that can result in positive or negative link polarity. The FWE nexus influences the AP parameters and creates causal loops, but these are beyond the scope of this study.

As local food production increases, the location of production simultaneously shifts across national borders. This fact touches on the problem of domestic and imported resource use and is, thus, a system boundary problem.

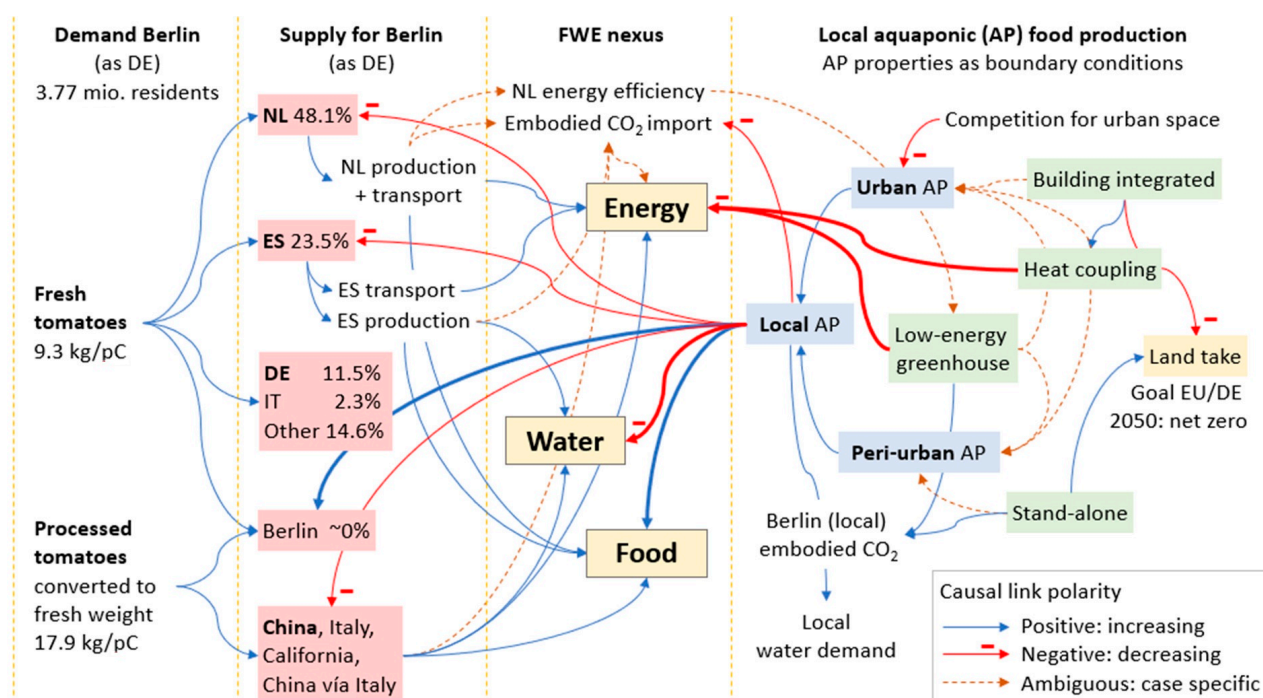
For example, the emission of greenhouse gases (GHG), for which its impact is indicated as GWP in the LCA approach, is an essential indicator for measuring climate sustainability. However, a country-specific CO<sub>2</sub> balance has some weaknesses: Germany emitted an estimated total of 805 Mt CO<sub>2</sub> equivalents in 2019, but almost as much (an estimated 797 Mt CO<sub>2</sub> equivalents) was emitted in the production of German imported goods in 2015 [74]. Offshoring environmental damages were also criticised concerning Europe's Green Deal [75], but, currently, the EC 2021 proposals for making the EU's policies fit for reducing net greenhouse gas emissions by at least 55% by 2030 [76] include a carbon border adjustment mechanism [77].

Comparably, local food production increases local resource use and thus impairs the 'local ecological footprint' while simultaneously reducing the footprint of distant production and possibly the overall ecological footprint.

The same applies to the water sector. A significant proportion of the tomatoes consumed in Berlin are produced on the Spanish Almeria peninsula around the town, El

Ejido. In this region, the rapid development of greenhouse horticulture since the 1950s has dramatically affected the availability of groundwater resources [78], which causes aquifer overexploitation. In addition, water quality deterioration occurs due to an increase in water salinity in aquifers as a result of marine intrusion processes and unsustainable aquifer management [72]. However, the share of water needed under these troublesome circumstances to cultivate tomato for export to Germany does not appear in the German water consumption statistics.

This study examines the boundary conditions for a production-location shift from other countries to Berlin based on year-round production. Compared to fish and lettuce, tomatoes have the quantitatively highest share of food production in the upscaled AP scenario (cf. Table 4), which is why tomato production is used to illustrate the dependencies of a production shift to Berlin as visualised in Figure 4.



**Figure 4.** Impact of simplified causal relations on the FWE nexus concerning year-round tomato production and aquaponic setup as boundary conditions for production-location shift; FWE ranking was conducted according to the main dependencies of the sectors; swim lanes are explained in Table 6.

Figure 4 contains subdivisions such as the so-called swim lanes which are explained in more detail in Table 6. The swim lane ‘local AP’ comprises urban and peri-urban AP, as they are both within the system boundaries of the circular city (CC). Baganz et al. [79] noted the potential for integrating AP into the CC through resource streams such as greywater, plant leftovers, and sewage; the diagram element ‘heat coupling’ in Figure 4 is related to this.

In terms of global environmental impacts and only these are considered in this study; relocation of production only makes sense if it reduces these impacts.

**Table 6.** Causal relations of significant tomato production-location variables.

Production Variables	Selected Causal Relationships
Demand Berlin	In 2018/2019, 9.3 kg/PC fresh tomatoes and 17.9 kg/PC processed tomatoes were consumed in Germany (DE); we assumed the same for Berlin.
Supply for Berlin	In 2019, the production shares on fresh tomatoes for Germany (DE) include the following: The Netherlands (NL) 48.1%, Spain (ES) 23.5%, DE 11.5%, and Italy (IT) 2.3% [80]. We assume that these values also apply to Berlin. The share of tomatoes produced in Berlin is not known. The footprint evaluation of processed tomato products is not the subject of this study; nevertheless, an LCA of packaged tomato puree exists in the literature [81]. All deliveries result in an import of embodied CO <sub>2</sub> . It should be noted that China is the globally most significant producer of tomatoes—some tomato products are distributed in the EU under an Italian label [82].
FWE nexus	The FWE ranking in Figure 4 indicates the main dependencies of the sectors: the climate crisis (CO <sub>2</sub> , <b>energy</b> ) is the greatest global challenge. If it is not solved, the global water balance will face significant problems and water scarcity will increase. Water, in turn, is the basis for all forms of <b>food</b> production.
Local aquaponic	Concerning urban AP, increasing building integration will reduce land consumption, which is required to achieve zero net land take by 2050 [83]. On the other hand, increasing competition for urban space will decrease urban AP applications. Peri-urban AP results in the conflict of objectives that, on the one hand, mitigates competition for use in the city but, on the other hand, is usually built as a standalone facility that results in increased land consumption. The high standard of the Dutch (NL) greenhouse production is the energy-related benchmark concerning greenhouse production in Berlin. Heat coupling and/or low-energy greenhouse are required for production in Berlin to have a lower impact on the energy sector than production in the Netherlands. Increasing local AP will induce the following: decrease imports, reduce embodied CO <sub>2</sub> , mitigate water scarcity in Almeria, and increase local food production. Due to the double use of water by AP, the overall water consumption will decrease (WCO in Table 5) but local water demand will increase.

## 4. Discussion

### 4.1. Food: Demand-Side Impact of Dietary Shifts

AP based food production meets the EU and global circular economy trends and creates possibilities for green entrepreneurship development [84]. The causal relationships shown so far are only a small part of the aquaponics-related impact structure. Two causalities shall be highlighted: (1) the impact of a ‘human’ pescatarian diet on GHG emissions and (2) the mitigation of phosphorus depletion by recycling the element by AP.

Agriculture is the primary driver of land system change, e.g., through tropical deforestation [85]. The food system also impacts biodiversity loss [86]—related to the biosphere integrity planetary boundary—and while domestic livestock currently has an estimated biomass of 100 Mt C, all wild mammals globally account for only about 7 Mt C [87]. Food systems are currently threatening human health and environmental sustainability [6] and environmental impacts can be reduced on the supply as well as on the demand side [88]. At the EU level, rapid changes in our habits and behaviour are requested [89] in order to reduce the environmental and climate footprint of the EU food systems [90]. The negative impact of meat consumption on the environment is well known [91]. Fish represents an alternative: global aquaculture has a rather modest share of approximately 0.49% of anthropogenic GHG emissions in 2017 [92] than terrestrial livestock farming (approximately 15%). Other alternatives include insects, which can be used both as fish feed [93] and as human feed, e.g., dried yellow mealworms [94]. A GHG emission tax on food products can support dietary shifts but must be introduced globally or trade restrictions must be considered to be fully efficient [95]. Concomitantly, environmentally harmful subsidies should be avoided [1]. The IPCC [96] investigated the role of dietary preferences and the demand-side GHG mitigation potential of different diets by 2050. A pescatarian diet consisting of seafood could save about 4.0 GtCO<sub>2</sub>-eq a<sup>−1</sup>, whereas a vegan diet without animal source food has a doubled effect of about 7.9 GtCO<sub>2</sub>-eq a<sup>−1</sup> [96]. The GHG savings potential of a pescatarian diet with a high share of freshwater fish would be between these two values. None of these scenarios will fully unfold, but one crucial aspect of the

food environment and the desirability of food is inter alia embossed by socio-cultural aspects [97], which can be changed.

However, changes in the diet affect not only CO<sub>2</sub> emissions but also many other components of the food system. Modern food production is entirely dependent on the non-renewable resource phosphorous (P) [98,99]: Biogeochemical flows—mainly nitrogen and phosphorous fluxes—are seen as a planetary boundary [100] and agriculture is a major driver exceeding it [8]. The use of phosphate causes the phosphorous dilemma: while mineral fertiliser facilitated the intensification of plant production [101,102], it has results in an enormous P-input into the biosphere [16] with P as a dominant driver of eutrophication with all its adverse effects [16]. Without P recycling, food security will inevitably be violated in the long run [103], preventing us from ‘living well, within the limits of our planet’ [104]. P recycling is also becoming increasingly crucial concerning circular cities and urban farming. In aquaculture and aquaponics, the treatment and recycling of potential P-sources are also of interest. After fish feeding, a considerable fraction of dietary P is not retained in fish but excreted and dissolved P is strongly adsorbed onto particles [105]. In RAS, solid waste from faeces and uneaten feed pellets represents a substantial reservoir of nutrients, especially P, and needs to be captured [106], e.g., by using drum filters or passive sedimenters. Therefore, efforts are focused on increasing nutrient retention in fish or using sludge as a nutrient sink in RAS [107]. Another possibility to increase the effectiveness of aquaponics in terms of P is the substitution of fishmeal and fish oil with other ingredients (algae and poultry meal). Such fish diets reduce the footprint for carnivorous finfish production [108], also regarding P [109].

#### 4.2. Water: Trans-Aquaponics

Concerning human food production, AP impacts the circular economy in a positive manner [60,61]. Following the circular economy concept, the CC consists of loops formed by NBS, which are defined as concepts derived from nature and focused on resource recovery [29]. AP is itself an NBS and the wastewater generated in the RAS, instead of being treated, can be provided as nutrient water for, e.g., a vertical green system (VGS) [79]. Systems based on the aquaponic principle that extend crop production from hydroponic to soil-based methods are referred to as trans-aquaponics [39]. Such a trans-aquaponic solution emerges when the two NBS units, in this case aquaculture and VGS, are coupled to tackle circularity challenges in cities [40].

While horizontal space is scarce and under tremendous utilisation pressure for use in densely built urban regions, vertical space—facades and walls—is rarely used apart from billboards and photovoltaic applications. VGS including expensive green walls, modular wall-mounted plant beds, or low-cost and sustainable facade greening including ground-based climbing plants are promoted for several ecosystem services and are simultaneously an aesthetic upgrade of buildings or passive cooling [110,111]. Food production is even possible on several height zones of the building facades and could include host vine-crops (i.e., climber species) such as kiwifruits or grapes and other suitable crops with artificial cropping adjustments for vegetables such as beans, tomatoes, cucumbers, and peppers; or fruits such as blackberries, blueberries, pears, or apples. Due to the negative climatic water balance, especially in the summer season, irrigation water sources and volumes are a significant factor in determining the sustainability of VGS. In Berlin, VGS would require 240 (north exposure) to 400 L m<sup>-2</sup> (south exposure) of water in summer, of which only 330 L m<sup>-2</sup> can be collected from the roof [112]. For the remaining 70 L m<sup>-2</sup>, the aquaculture wastewater from a RAS can be used because it does not contain any human faeces or human-active pharmaceuticals. Vertical green could also be integrated into the aquaculture system itself by mostly bringing closed production into open space and allowing the multi functionalities described above. Transporting water through pumps may reduce the sustainability benefits of aquaculture water compared to tap water and fertiliser. The biggest challenge in irrigation is the storage of AP waters in terms of fouling and space demand.



In 2040, the expected water consumption of Berlin amounts to 806 million m<sup>3</sup> (cf. Table 7) out of which 103 million m<sup>3</sup> are attributable to industry and trade. The reduction in water consumption by 2.0 million m<sup>3</sup> (cf. Table 5) corresponds to about 2% of the latter demand. This value could be further increased if water losses due to evapotranspiration were regained and condensed by cooling traps and eventually fed into the aquaculture unit [113].

**Table 7.** Estimated water consumption in Berlin in the year 2040, author's work based on water supply concept for Berlin [114].

Water 2040	(Million m <sup>3</sup> )
Households	551.0
Industry and trade	102.6
Others	140.6
Environment	11.4
Total	805.6

The implementation process for upscaled aquaponics will take some time and result in higher water demand in the future due to AP water demand. Berlin's water management faces challenges, e.g., concerning groundwater extraction as shown by a lawsuit filed by the Berlin State Working Group for Nature Conservation to protect peatlands and wetlands [115]. In the future, these challenges will increase and new concepts and courses of action will be required [116]. AP upscaling mitigates the water problem in the Almeria region but exacerbates it in the Berlin area. As urban agriculture, including aquaponics, claims access to water as a resource, care must be taken and the use of modern semi-closed greenhouses with condensation regaining [117] can contribute to care.

#### 4.3. Energy: Low-Energy Greenhouses and Transport Trade-Offs

The comparative-LCA has revealed the energetic disadvantages of greenhouse production in the moderate continental climate of the Berlin area, especially during the winter, compared to the Mediterranean climate in southern Europe. However, in cooler regions, the crop can be cultivated year-round without the need for a summer break or intensive and water consuming cooling as is required in southern Europe. Energy savings from upscaled urban aquaponics are limited when using a standard greenhouse. Winter heating in regions such as Berlin can be supported by excess heat. On the other hand, there are technical solutions for greenhouse crop production for almost all climatic situations [118]. Upgrading greenhouses with a package of high-technological equipment such as combined heat and power units, heat pumps, underground seasonal and daytime energy storage systems, and air treatment units as used in the closed greenhouse concept [119] can strongly reduce energy consumption [117]. In order to achieve optimal energy saving and plant production, smart decision support systems and/or model-based climate control systems for the greenhouse crop production units (or closed units) are needed [120].

Another energy-related aspect is that the environmental impact of food transport is often reduced to its CO<sub>2</sub> emissions, which are the so-called food miles, and this accounts for only a tiny part of its environmental impact [121]. Here, trade-offs between energy, water, and food transport (FWE nexus) must be considered. For example, an LCA case study of tomatoes originating in Morocco and imported into France reveals that a comprehensive method for assessing freshwater use impacts is lacking for the energy and water trade-off [122]. Furthermore, traffic-related non-exhaust particulate matter contributes significantly to the flux of microplastics into the environment [123] and tire and brake abrasion particles are transported globally through the atmosphere to distant regions [124]. Nota bene: these problems are not addressed by a tax on GHG emissions from transportation.



#### 4.4. Strategy: Using Climate Zones Advantages

Up to this point, we have considered a scenario that assumes full coverage of fish/tomato/lettuce demand by Berlin-based production. Consequently, Spain's share of 23.5% of fresh tomatoes available in Berlin in 2019 would be reduced to zero. However, this leaves untapped opportunities that could arise from the different climate zones in which the Almeria peninsula and Berlin are located. The comparative-LCA covers a year but even when including the cold season, the exploitation of AP achieves an environmental impact improvement in all 12 categories (cf. Figure 2). This impact could be further reduced if climatic conditions were exploited locally on a seasonal basis, i.e., produced in the natural production season and consumed within the same climatic zone [125]. An LCA of vegetable production in Switzerland found significant seasonal effects due to the different methods in which tomatoes are produced: 0.2 kg CO<sub>2</sub>/kg when grown outdoors in Switzerland in summer, 0.5 kg CO<sub>2</sub>/kg when grown in Almeria and transported to Switzerland, and 5 kg CO<sub>2</sub>/kg (25 times as much) in a greenhouse in Switzerland heated with fossil fuels [126].

A scenario that assumes that not all tomato production takes place in Berlin should consider the following points for trade-offs: (1) in Almeria, water stress increases significantly in summer and production breaks are common; (2) in Berlin, heating and lighting requirements increase significantly in winter and results in high heat and power consumption; and (3) fresh tomato cultivars contain over 95% water and so tomato transport becomes water transport. Tomato products were not included in the calculation of the impact of upscaled-AP scenario because the underlying comparative-LCA did not cover them, but it can be assumed that the water content of processed tomatoes is lower than that of fresh tomatoes and thus transportation has a lower environmental impact.

A strategy that optimally adapts consumption patterns, thereby taking advantage of climatic zones, would decrease total tomato production in Almeria and, consequently, exports to Germany. Fresh tomatoes from Almeria would be supplied in winter, while tomato products would be produced and exported in summer. In turn, fewer fresh tomatoes but more tomato products would be produced and consumed in Berlin during the winter, while in summer all fresh tomato demand would be produced in the city. Trans-aquaponic VGSs operated by urban gardening communities would complement the seasonal fruit and vegetable supply.

## 5. Conclusions

This study uses aquaponics (AP) as an example to examine in detail what it means when a nature-based solution (NBS) is upscaled in the circular city (CC). Both the internal processes of the AP (NBS are often considered black boxes in CC context) and the effects of a production-location shift are examined to unveil and understand causal relations and dependencies of this part of the food system. The focus is on two goals: Reducing global environmental impact and zero net land take by 2050 in Germany.

Using the metropolis of Berlin as a case study, an upscaled-AP scenario was modelled based on the total fish demand to meet the required annual yield, with four different combinations of fish (catfish and tilapia) and plants (tomato and lettuce). The resulting fish/plant harvest ratios were catfish/tomato (1:3.3), catfish/lettuce (1:10.2), tilapia/tomato (1:11.1), and tilapia/lettuce (1:56.2). The share of each aquaponic setup in the upscaled-AP scenario was balanced such that the aquaponically produced fish and vegetables met the total demand of the city of Berlin. It was shown that the city's needs could be met locally. In order to produce these foods, about 370 AP facilities are required which requires a total area of 224 hectares.

The upscaled-AP scenario can make a relevant contribution to sustainability in Berlin. Increasing local AP will increase local food production, reduce environmental impacts associated with importing food, and decrease overall water consumption. Local AP mitigate water scarcity in Almeria but concomitantly increases local water demand in Berlin. As a predominant effect in terms of water, AP production of fresh tomatoes and lettuce in Berlin would save about 2.0 million m<sup>3</sup> of water compared with the German

import mix of tomato/lettuce. This corresponds to about 2% of Berlin's expected water consumption of 103 million m<sup>3</sup> related to industry and trade in 2040. If processed tomatoes were considered here, the effect would be even higher. An essential prerequisite for this year-round production scenario is building integration for the thermal coupling needed in the colder season. The heating demand can be significantly reduced by using low-energy greenhouses.

We identified significant AP variables which affect the three sectors of the FWE nexus, either directly or through causal chains, which are useful for controlling environmental impacts when planning or operating an AP. In order to analyse the supply-side causal relations of a production shift to Berlin, we elaborated production-site dependent causal links to the FWE nexus, which mainly include climatic conditions, water availability, and transportation. A moderate 'climate zones advantage scenario' with FWE nexus related trade-offs (winter tomatoes from Spain, summer tomatoes from Berlin) is discussed. A production-locations shift should reduce environmental impacts and, to achieve this, many boundary conditions must be taken into account. These conditions include the following: The impact on climate should be at least at the same level as abroad, embodied CO<sub>2</sub> should be included, and the environmental impact of food transport (food miles) should not only be reduced to CO<sub>2</sub> emission but should also comprise other effects, e.g., abrasion of tire particles. Concerning spatial impacts, it can be stated that 'building integration' of urban AP (inside buildings or on the rooftop) reduces land consumption while peri-urban AP mitigates competition for urban space. On the other hand, peri-urban AP results in a conflict of objectives: if realised as standalone facilities, it will increase land consumption, which contradicts the zero net land take by 2050.

There is a possibility that an upscaled-AP scenario will boost the demand for freshwater fish in Berlin. The approximate global GHG savings potential according to IPCC [96] is calculated to be 4.0 GtCO<sub>2</sub>-eq a<sup>-1</sup> for seafood diets and 7.9 GtCO<sub>2</sub>-eq a<sup>-1</sup> for a vegan diet. A pescatarian diet with a high share of freshwater fish would fall between these two values and could have a more substantial impact than the relocation of production sites or the application of aquaponics technology.

However, in order to decide whether urban AP makes sense or not, a close look at other factors beyond environmental considerations is required, e.g., redirecting some of the EU's substantial agricultural subsidies to urban agriculture would positively impact on the economics of AP.

An external perspective may also be helpful, e.g., regulations on AP in the UK should be monitored and positive developments adopted in the EU [127]. Urban AP supports the circular city concept but competes with other uses for limited space. Therefore, further research is required to find suitable sites for local AP in Berlin, in proximity of CC resources, possibly on the urban roofscape, or in peri-urban areas. From a broader perspective, the presented research and case study outcomes can contribute to the conceptual approach of international pilot projects for urban socio-economic innovative and inclusive network development based on green circularity and sustainability.

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## Appendix A

**Table A1.** Causal relations of significant aquaponic variables.

Aquaponic Variables	Selected Causal Relationships
Cooling	Cooling lowers the greenhouse temperature, which requires energy and generates excess heat depending on the technology.
Coupling degree—energy	Thermal connections between the AP units can reduce the total energy demand of the AP.
Coupling degree—nutrient	In a well-balanced AP, a high nutrient coupling degree reduces fertiliser consumption to a minimum. The double use of water is at the core of the aquaponic principle and a high water coupling degree is the objective of a well-balanced AP. It reduces both the external water consumption of the HP and the wastewater generation of the facility.
Coupling degree—water	Electricity is mainly used for pumps, control systems, lighting, and heating of RAS process water. Thus, these components directly affect the energy sector of the nexus through their operating times and energetic efficiency.
Electricity	Feed conversion rate (FCR) describes the conversion of feed into biomass.
Feed conversion rate	Fertiliser is essential for optimal plant growth; over-fertilisation defects are not considered here.
Fertiliser	Fish production contributes to the food sector; its farming generates sludge. The amount of wastewater should be as low as possible, but zero is a difficult goal to achieve. If the production of freshwater fish in RAS were to replace marine fish production in net-cages then the phosphorus flux into the sea could be reduced.
Freshwater fish	Fish feed is the prerequisite for fish growth and the type and quality of feed also affect FCR. Freshwater fish can be divided into three groups according to their temperature requirements: tropical, warm water, and cold-water fish, which determines the water temperature of the aquaculture unit. For different fish species, different stocking densities are allowed: e.g., tilapia max. 100 kg/m <sup>3</sup> or catfish with up to 400 kg/m <sup>3</sup> . In addition, the species influences the FCR.
Fish feed	Fish feed without fish meal and fish oil reduces phosphorus removal from the oceans by wild fisheries among other positive environmental aspects [108]; insects can be part of fish diets [128]; and the impact on the quality of fish feed is case-specific.
Fish species	O <sub>2</sub> is used in RAS to increase yield and ensure the minimum oxygen content in the water in critical situations. CO <sub>2</sub> is used in HP greenhouse production to increase yield. The gases can be exchanged between both AP units [129].
Fish-free feed	Greenhouse temperature influences plant growth with positive link polarity.
Gas: CO <sub>2</sub> and O <sub>2</sub>	Heating is needed for tropical fish and greenhouses, especially in the colder season.
Greenhouse temperature	Greenhouse lighting requires electrical energy; it can also contribute to heating if, e.g., heat-emitting sodium vapour lamps are used. LED lamps do not emit long-wave heat and contribute to greenhouse heating to a lesser extent.
Heating	In the winter season, plant production in the greenhouse can be suspended, which saves energy for lighting and heating, but at the same time reduces the yield of crop production.
Lighting	The plant species affects the type and quantity of fertiliser needed, the required greenhouse temperature, the water uptake, the harvest yield, and their dynamics.
Plant productionwinter break	Increased harvest contributes positively to the food sector. Plants take up water, transpire it, and the water vapour can be regained in modern greenhouse systems. Depending on the irrigation method, wastewater is produced, e.g., for flushing the plant troughs.
Plant species	
Plants	

Table A1. Cont.

Aquaponic Variables	Selected Causal Relationships
Sludge	The quantity and composition of the sludge determine how much of it can be recycled.
Sludge recycling	Sludge removal and mineralisation can save fertiliser and thus reduce the use of phosphorous as a supplemental fertiliser.
Stocking density	Stocking density affects both FCR and the amount of fish that can be harvested and the requirements for additional oxygen or improved water treatment.
Wastewater	Wastewater is the water leaving the facility. All internal water flows are not included. In particular, the nutrient water is not considered wastewater, as suggested by Baganz et al. [39].
Water regain for reflux	The more plants are cultivated, the more energy is needed to regain the evapotranspired water in the greenhouse, which in turn saves the water needed in the aquaculture unit.
Water temperature	Fish are poikilothermic; unlike homoeothermic animals, they do not use their metabolisms to heat or cool themselves. They can therefore invest more energy into growth, resulting in a higher FCR. However, in a temperate climate zone, the water for tropical fish must be heated, which means that the energy saved internally by fish must be supplied externally.

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