Causalities of Upscaled Urban Aquaponics

Subjects: Urban Studies

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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 m3 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

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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].

2. Analysis on Results

2.1. 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 [38]. 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 [39]. For freshwater fish, the shares was 3 kg/pC and 0.9 kg/PC for freshwater fish products [40]. 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 [41], 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 1**).

Table 1. 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 (kg/PC)	Products (kg/PC)	Total (kg/PC)	Netto (t)	Not Marketable	Brutto (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
	fresh tomato only			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 2**). 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 3**).

Table 2. 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 3. 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*	107,670	26,918		
			delta	750	464		
fish demand	20,584						
fish yield	20,584			*) fish/plant harvest ratio			
delta	0			**) AP 4 excluded because of the F/P ratio			

2.2. 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 3**).

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 3**). 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 4**) 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 4. 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 [42].

LCA Impact Category	Abbr.	Unit	Tomato, Fresh		mio. packs	73.6	Lettuce		mio. packs	179.5	Total Reduction	
			Mix-DE	Rooftop AP	Delta	Less Impact	Mix-DE	Rooftop AP	Delta	Less Impact		
Global warming potential 100	GWP100	kg CO_2 eq	0.5760	0.5261	0.0500	3679662	0.0769	0.0385	0.0383	2822799	6502	t
Water consumption	WCO	m^3	0.0142	−0.0101	0.0243	1786533	0.0033	−0.0002	0.0035	261272	2,047,805	m^3
Water scarcity	WSI	m^3	0.0109	−0.0059	0.0168	1237314	0.0021	−0.0001	0.0022	163054	1,400,368	m^3

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 [43].

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_2 footprint (GWP100 in **Table 4**) by 7691 t CO_2-equivalents. This result can be significantly improved by using aquaponics-integrated microgrids (so-called smarthoods) where all FWE flows are circularly connected [44].

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 1**).

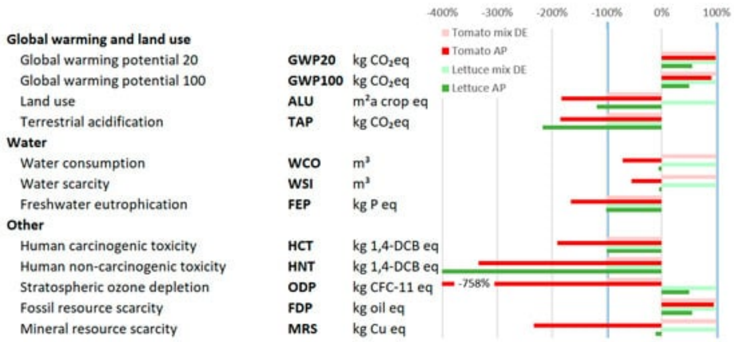

Figure 1. Relative change in LCA impact categories for optimised rooftop-aquaponics (AP) compared to the German market mix for fresh tomatoes and lettuce (mix DE) as +/− 100%; authors work and the calculation based on data from comparative-LCA [42].

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_2 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 1**).

2.3. 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 2**). 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.

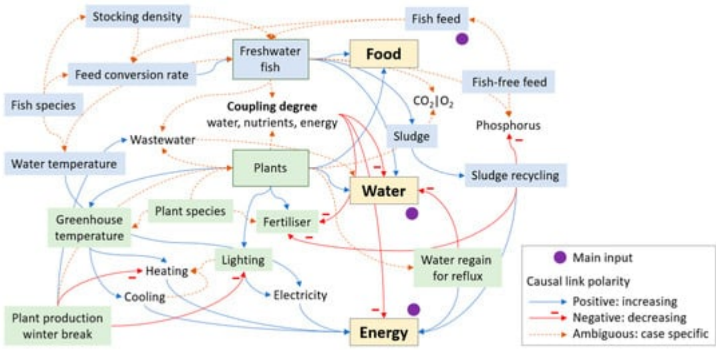

Figure 2. Impact of causal chains—formed by significant aquaponic variables—on FWE-Nexus (no flow chart; no functional scheme of an AP); the variables are explained in **Table A1**.

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.
Coupling degree—water	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.
Electricity	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.
Feed conversion rate	Feed conversion rate (FCR) describes the conversion of feed into biomass.
Fertiliser	Fertiliser is essential for optimal plant growth; over-fertilisation defects are not considered here.
Freshwater fish	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.
Fish feed	Fish feed is the prerequisite for fish growth and the type and quality of feed also affect FCR.
Fish species	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^3 or catfish with up to 400 kg/m^3. In addition, the species influences the FCR.
Fish-free feed	Fish feed without fish meal and fish oil reduces phosphorus removal from the oceans by wild fisheries among other positive environmental aspects [45]; insects can be part of fish diets [46]; and the impact on the quality of fish feed is case-specific.
Gas: CO_2 and O_2	O_2 is used in RAS to increase yield and ensure the minimum oxygen content in the water in critical situations. CO_2 is used in HP greenhouse production to increase yield. The gases can be exchanged between both AP units [47].
Greenhouse temperature	Greenhouse temperature influences plant growth with positive link polarity.
Heating	Heating is needed for tropical fish and greenhouses, especially in the colder season.
Lighting	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.
Plant productionwinter break	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.

Aquaponic Variables	Selected Causal Relationships
Plant species	The plant species affects the type and quantity of fertiliser needed, the required greenhouse temperature, the water uptake, the harvest yield, and their dynamics.
Plants	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.
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. [48].
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.

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 2** is a graphical representation of the causal chains formed by the AP variables.

The connectors in **Figure 2** 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 results 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_2 balance has some weaknesses: Germany emitted an estimated total of 805 Mt CO_2 equivalents in 2019, but almost as much (an estimated 797 Mt CO_2 equivalents) was emitted in the production of German imported goods in 2015 [49]. Offshoring environmental damages were also criticised concerning Europe’s Green Deal [50], 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 [51] include a carbon border adjustment mechanism [52].

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 [53], 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 [43]. 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 3**), which is why tomato production is used to illustrate the dependencies of a production shift to Berlin as visualised in **Figure 3**.

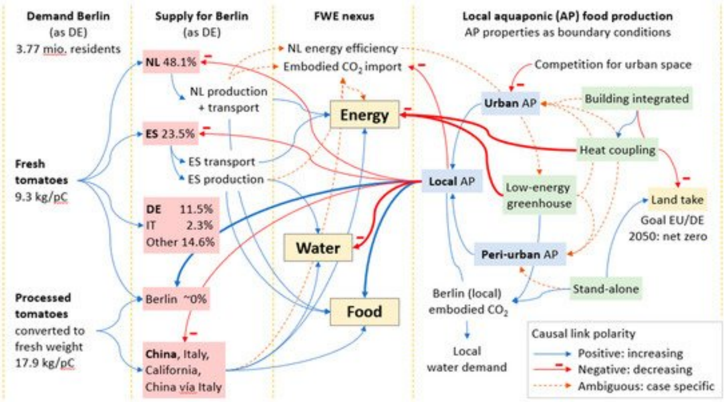

Figure 3. Impact of simplified causal relations on the FWE nexus concerning year-round tomato production and aquaponic setup as boundary conditions for production-location shift; FWE ranking was conducted according to the main dependencies of the sectors; swim lanes are explained in **Table 5**.

Figure 3 contains subdivisions such as the so-called swim lanes which are explained in more detail in **Table 5**. 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. [54] 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 3** is related to this.

Table 5. 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% [55]. 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 [56]. All deliveries result in an import of embodied CO_2. 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 [57].**
FWE nexus	**The FWE ranking in Figure 4 indicates the main dependencies of the sectors: the climate crisis (CO_2, energy) 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 food production.**
Local aquaponic	**Concerning urban AP, increasing building integration will reduce land consumption, which is required to achieve zero net land take by 2050 [58]. 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_2, 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.**

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.

3. Current Insights

3.1. 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 [59]. 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 [60]. The food system also impacts biodiversity loss [61]—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 [62]. 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 [63]. At the EU level, rapid changes in our habits and behaviour are requested [64] in order to reduce the environmental and climate footprint of the EU food systems [65]. The negative impact of meat consumption on the environment is well known [66]. Fish represents an alternative: global aquaculture has a rather modest share of approximately 0.49% of anthropogenic GHG emissions in 2017 [67] than terrestrial livestock farming (approximately 15%). Other alternatives include insects, which can be used both as fish feed [68] and as human feed, e.g., dried yellow mealworms [69]. 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 [70]. Concomitantly, environmentally harmful subsidies should be avoided [1]. The IPCC [71] 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 $GtCO_2$-eq a^{-1}, whereas a vegan diet without animal source food has a doubled effect of about 7.9 $GtCO_2$-eq a^{-1} [71]. 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 [72], which can be changed.

However, changes in the diet affect not only CO_2 emissions but also many other components of the food system. Modern food production is entirely dependent on the non-renewable resource phosphorous (P) [73][74]: Biogeochemical flows—mainly nitrogen and phosphorous fluxes—are seen as a planetary boundary [75] 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 [76][77], 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 [78], preventing us from ‘living well, within the limits of our planet’ [79]. 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 [80]. In RAS, solid waste from faeces and uneaten feed pellets represents a substantial reservoir of nutrients, especially P, and needs to be captured [81], 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 [82]. 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 [45], also regarding P [83].

3.2. Water: Trans-Aquaponics

Concerning human food production, AP impacts the circular economy in a positive manner [84][85]. 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) [54]. Systems based on the aquaponic principle that extend crop production from hydroponic to soil-based methods are referred to as trans-aquaponics [48]. 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 [86].

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 [87][88]. 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^{-2} (south exposure) of water in summer, of which only 330 L m^{-2} can be collected from the roof [89]. For the remaining 70 L m^{-2}, 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^3 (cf. **Table 6**) out of which 103 million m^3 are attributable to industry and trade. The reduction in water consumption by 2.0 million m^3 (cf. **Table 4**) 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 [90].

Table 6. Estimated water consumption in Berlin in the year 2040, author’s work based on water supply concept for Berlin [91].

Water 2040	(Million m^3)
Households	**551.0**
Industry and trade	**102.6**

Water 2040	(Million m^3)
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 [92]. In the future, these challenges will increase and new concepts and courses of action will be required [93]. 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 [94] can contribute to care.

3.3. 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 [95]. 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 [96] can strongly reduce energy consumption [94]. 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 [97].

Another energy-related aspect is that the environmental impact of food transport is often reduced to its CO_2 emissions, which are the so-called food miles, and this accounts for only a tiny part of its environmental impact [98]. 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 [99]. Furthermore, traffic-related non-exhaust particulate matter contributes significantly to the flux of microplastics into the environment [100] and tire and brake abrasion particles are transported globally through the atmosphere to distant regions [101]. Nota bene: these problems are not addressed by a tax on GHG emissions from transportation.

References

1. UNEP. Making Peace with Nature—A Scientific Blueprint to Tackle the Climate, Biodiversity and Pollution Emergencies; UNEP: Nairobi, Kenya, 2021; ISBN 978-92-807-3837-7.
2. UN. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (accessed on 10 May 2018).
3. UN. The Sustainable Development Goals Report 2020; UN: New York City, NY, USA, 2020; ISBN 978-92-1-101425-9.
4. UN. Decade of Action—Ten Years to Transform Our World. Available online: https://www.un.org/sustainabledevelopment/decade-of-action/ (accessed on 24 March 2021).
5. BReg. Deutsche Nachhaltigkeitsstrategie—Weiterentwicklung 2021. 2021. Available online: https://www.bundesregierung.de/breg-de/service/publikationen/deutsche-nachhaltigkeitsstrategie-weiterentwicklung-2021-langfassung--1875178 (accessed on 26 March 2021).
6. Willett, W.; Rockström, J.; Loken, B.; Springmann, M.; Lang, T.; Vermeulen, S.; Garnett, T.; Tilman, D.; DeClerck, F.; Wood, A.; et al. Food in the Anthropocene: The EAT–Lancet Commission on Healthy Diets from Sustainable Food Systems. Lancet 2019, 393, 447–492.
7. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S., III; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecol. Soc. 2009, 14, 1–33.
8. Campbell, B.M.; Beare, D.J.; Bennett, E.M.; Hall-Spencer, J.M.; Ingram, J.S.; Jaramillo, F.; Ortiz, R.; Ramankutty, N.; Sayer, J.A.; Shindell, D. Agriculture Production as a Major Driver of the Earth System Exceeding Planetary Boundaries. Ecol. Soc. 2017, 22.
9. Link, J.S.; Watson, R.A. Global Ecosystem Overfishing: Clear Delineation within Real Limits to Production. Sci. Adv. 2019, 5, eaav0474.
10. FAO. The State of World Fisheries and Aquaculture 2018; FAO: Rome, Italy, 2018.

11. Franks, B.; Ewell, C.; Jacquet, J. Animal Welfare Risks of Global Aquaculture. Sci. Adv. 2021, 7, eabg0677.
12. Naylor, R.L.; Goldburg, R.J.; Primavera, J.H.; Kautsky, N.; Beveridge, M.C.M.; Clay, J.; Folke, C.; Lubchenco, J.; Mooney, H.; Troell, M. Effect of Aquaculture on World Fish Supplies. Nature 2000, 405, 1017–1024.
13. Naylor, R.L.; Hardy, R.W.; Buschmann, A.H.; Bush, S.R.; Cao, L.; Klinger, D.H.; Little, D.C.; Lubchenco, J.; Shumway, S.E.; Troell, M. A 20-year Retrospective Review of Global Aquaculture. Nature 2021, 591, 551–563.
14. Holmer, M. Environmental Issues of Fish Farming in Offshore Waters: Perspectives, Concerns and Research Needs. Aquac. Environ. Interact. 2010, 1, 57–70.
15. Barrett, L.T.; Swearer, S.E.; Dempster, T. Impacts of Marine and Freshwater Aquaculture on Wildlife: A Global Meta-Analysis. Rev. Aquac. 2019, 11, 1022–1044.
16. Huang, Y.; Ciais, P.; Goll, D.S.; Sardans, J.; Peñuelas, J.; Cresto-Aleina, F.; Zhang, H. The Shift of Phosphorus Transfers in Global Fisheries and Aquaculture. Nat. Commun. 2020, 11.
17. Guzmán-Luna, P.; Gerbens-Leenes, P.W.; Vaca-Jiménez, S.D. The Water, Energy, and Land Footprint of Tilapia Aquaculture in Mexico, a Comparison of the Footprints of Fish and Meat. Resour. Conserv. Recycl. 2021, 165, 105224.
18. UNESCO. The United Nations World Water Development Report. Wastewater: The Untapped Resource. 2017. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000247153 (accessed on 27 April 2021).
19. UN-Water. Summary Progress Update 2021: SDG 6—Water and Sanitation for All. 2021. Available online: File:///C:/Users/Research/AppData/Local/Temp/SDG-6-Summary-Progress-Update-2021_Version-2021-03-03-1.pdf (accessed on 27 April 2021).
20. Naegel, L.C.A. Combined Production of Fish and Plants in Recirculating Water. Aquaculture 1977, 10, 17–24.
21. Rakocy, J.E.; Masser, M.P.; Losordo, T.M. Recirculating Aquaculture Tank Production Systems: Aquaponics—Integrating Fish and Plant Culture. SRAC Publications. 454; Texas A&M University: College Station, TX, USA; Southern Regional Aquaculture Center: Stoneville, MS, USA, 2006; Available online: https://srac.tamu.edu/fact-sheets/serve/105 (accessed on 24 April 2018).
22. Joyce, A.; Goddek, S.; Kotzen, B.; Wuertz, S. Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources. In Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future; Goddek, S., Joyce, A., Kotzen, B., Burnell, G.M., Eds.; Springer International Publishing: Basel, Switzerland, 2019.
23. UN. UN Deputy Secretary-General at Mayor's Forum—Press Release. 2015. Available online: https://www.un.org/press/en/2015/dsgsm874.doc.htm (accessed on 14 December 2018).
24. UN-Habitat. World Cities Report 2016. 2016. Available online: https://unhabitat.org/sites/default/files/download-manager-files/WCR-2016-WEB.pdf (accessed on 27 April 2021).
25. IMM. Implementing the New Leipzig Charter through Multi-level Governance: Next Steps for the Urban Agenda for the EU. 2020. Available online: https://ec.europa.eu/regional_policy/sources/docgener/brochure/new_leipzig_charter/new_leipzig_charter_implem_en.pdf (accessed on 28 December 2020).
26. IMM. The New Lepzig Charte—The Transformative Power of Cities for the Common Good. 2020. Available online: https://www.bmi.bund.de/SharedDocs/downloads/EN/eu-presidency/gemeinsame-erklaerungen/new-leipzig-charta-2020.pdf (accessed on 12 January 2021).
27. CE, TNO, FABRIC. Amsterdam Circular—Vision and Roadmap for the City and Region. Available online: https://assets.website-files.com/5d26d80e8836af2d12ed1269/5ede5a03e4cd056426b86d8b_20152115%20-%20Amsterdam%20scan%20-%20report%20EN%20web%20single%20page%20-%20297x210mm.pdf (accessed on 4 April 2018).
28. Sukhdev, A.; Vol, J.; Brandt, K.; Yeoman, R. Cities in the Circular Economy: The Role of Digital Technology. 2019. Available online: https://www.ellenmacarthurfoundation.org/assets/downloads/Cities-in-the-Circular-Economy-The-Role-of-Digital-Tech.pdf (accessed on 30 January 2020).
29. Langergraber, G.; Pucher, B.; Simperler, L.; Kisser, J.; Katsou, E.; Buehler, D.; Mateo, M.C.G.; Atanasova, N. Implementing Nature-Based Solutions for Creating a Resourceful Circular City. Blue-Green Syst. 2020, 2, 173–185.
30. Science for Environment Policy. The Solution is in Nature; Science Communication Unit, University of the West of England (UWE): Bristol, UK, 2021.
31. IUCN. IUCN Global Standard for Nature-Based Solutions: A User-Friendly Framework for the Verification, Design and Scaling up of NbS, 1st ed.; IUCN: Gland, Switzerland, 2020.
32. UNEP. Adaptation Gap Report 2020; UNEP: Nairobi, Kenya, 2021; ISBN 978-92-807-3834-6.
33. Atanasova, N.; Castellar, J.A.C.; Pineda-Martos, R.; Nika, C.E.; Katsou, E.; Istenič, D.; Pucher, B.; Andreucci, M.B.; Langergraber, G. Nature-Based Solutions and Circularity in Cities. Circ. Econ. Sustain. 2021.
34. Castellar, J.A.C.; Popartan, L.A.; Pueyo-Ros, J.; Atanasova, N.; Langergraber, G.; Säumel, I.; Corominas, L.; Comas, J.; Acuna, V. Nature-based Solutions in the Urban Context: Terminology, Classification and Scoring for Urban Challenges and Ecosystem Services. Sci. Total Environ. 2021, 779, 146237.

35. Lohrberg, F.; Licka, L.; Scazzosi, L.; Timpe, A. Urban Agriculture Europe. 2015: 256. Architecture Urban Space. 2015. Available online: http://urban-agriculture-europe.org/files/urbanagricultureeurope_en.pdf (accessed on 16 February 2021).

36. Canet-Martí, A.; Pineda-Martos, R.; Junge, R.; Paço, T.A.; Bohn, K.; Delgado, C.; Pedras, C.M.G.; Alencikiene, G.; Skar, S.L.G.; Baganz, G.F.M. Nature-based Solutions for Urban Agriculture in Circular Cities: Challenges, Gaps and Opportunities. Water 2021. Unpublished work.

37. MUFPP. Milan Urban Food Policy Pact. 2015. Available online: https://www.milanurbanfoodpolicypact.org/wp-content/uploads/2020/12/Milan-Urban-Food-Policy-Pact-EN.pdf (accessed on 16 February 2021).

38. BLE. SJT-4040300-2019.xlsx Versorgung mit Gemüse nach Arten. Federal Office of Agriculture and Food (BLE). 2020. Available online: https://www.bmel-statistik.de/ernaehrung-fischerei/tabellen-kapitel-d-und-hiv-des-statistischen-jahrbuchs/ (accessed on 14 November 2020).

39. BLE. Ein- und Ausfuhr Tomaten Deutschland 2014–2018. 2019. Available online: https://www.bmel-statistik.de/fileadmin/daten/GBG-0050317-2018.pdf (accessed on 29 November 2020).

40. FIZ. Fischereiwirtschaft, Daten und Fakten 2020. 2020. Available online: https://www.fischinfo.de/images/broschueren/pdf/FIZ_Daten_und_Fakten_2020.pdf (accessed on 6 February 2020).

41. AfS. Berlins Einwohnerzahl stagniert 2020—Pressemitteilung Nr. 32. 2021. Available online: https://download.statistik-berlin-brandenburg.de/70fd75104b57d0fa/83cc240d450f/21-02-10.pdf (accessed on 10 February 2021).

42. Körner, O.; Bisbis, M.B.; Baganz, G.F.M.; Baganz, D.; Staaks, G.B.O.; Monsees, H.; Goddek, S.; Keesman, K.J. Environmental Impact Assessment of Local Decoupled Multi-Loop Aquaponics in an Urban Context. J. Clean. Prod. 2021, 313, 127735.

43. Castro, A.J.; López-Rodríguez, M.D.; Giagnocavo, C.; Gimenez, M.; Céspedes, L.; Calle, A.L.; Gallardo, M.; Pumares, P.; Cabello, J.; Rodriguez, E.; et al. Six Collective Challenges for Sustainability of Almería Greenhouse Horticulture. Int. J. Environ. Res. Public Health 2019, 16, 4097.

44. De Graaf, F.; Goddek, S. Smarthoods: Aquaponics Integrated Microgrids. In Aquaponics Food Systems; Springer International Publishing: Basel, Switzerland, 2019; pp. 379–392.

45. Meigs, H.; Barrows, F.; Sims, N.A.; Alfrey, K. Testing Diets without Fishmeal and Fish Oil for Kampachi. 2021. Available online: https://www.aquaculturealliance.org/advocate/testing-diets-without-fishmeal-and-fish-oil-for-kampachi/ (accessed on 26 April 2021).

46. Tran, G.; Heuzé, V.; Makkar, H. Insects in Fish Diets. Anim. Front. 2015, 5, 37–45.

47. Körner, O.; Gutzmann, E.; Kledal, P.R. A Dynamic Model Simulating the Symbiotic Effects in Aquaponic Systems; International Society for Horticultural Science (ISHS): Leuven, Belgium, 2017; pp. 309–316.

48. Baganz, G.F.M.; Junge, R.; Portella, M.C. The Aquaponic Principle—It is all about Coupling. Rev. Aquac 2021, in press.

49. BMU. Klimaschutz in Zahlen—Fakten, Trends und Impulse Deutscher Klimapolitik. 2020. Available online: https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutz_zahlen_2020_broschuere_bf.pdf (accessed on 4 December 2020).

50. Fuchs, R.; Brown, C.; Rounsevell, M. Europe's Green Deal Offshores Environmental Damage to Other Nations. Nature 2020, 586, 671–673.

51. EC. European Green Deal: Commission Proposes Transformation of EU Economy and Society to Meet Climate Ambitions. 2021. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541 (accessed on 14 July 2021).

52. EC. Proposal for a Establishing a Carbon Border Adjustment Mechanism—COM(2021) 564 Final. 2021. Available online: https://ec.europa.eu/info/sites/default/files/carbon_border_adjustment_mechanism_0.pdf (accessed on 14 July 2021).

53. Torrellas, M.; Antón, A.; López, J.C.; Baeza, E.J.; Parra, J.P.; Munoz, P.; Montero, J.I. LCA of a Tomato Crop in a Multi-Tunnel Greenhouse in Almeria. Int. J. Life Cycle Assess. 2012, 17.

54. Baganz, G.F.M.; Proksch, G.; Kloas, W.; Lorleberg, W.; Baganz, D.; Staaks, G.; Lohrberg, F. Site Resource Inventories—A Missing Link in the Circular City's Information Flow. Adv. Geosci. 2020, 54, 23–32.

55. BLE. Tomaten Weiterhin Sehr Beliebt. 2020. Available online: https://www.ble.de/SharedDocs/Downloads/DE/Pressemitteilungen/2020/200702_Tomaten.pdf;jsessionid=D4D2B52C65146BF0FC9C62A4 __blob=publicationFile&v=2 (accessed on 4 July 2020).

56. Vignali, G.; Manfredi, M. Life Cycle Assessment of a Packaged Tomato Puree: A Comparison of Environmental Impacts Produced by Different Life Cycle Phases. J. Clean. Prod. 2014, 73, 275–284.

57. Bizzotto, M. Tomato Derivatives: Increased Imports from China, Endangering Consumers' Health. Request for Mandatory Indication of Origin on Labels. Available online: https://www.europarl.europa.eu/doceo/document/E-8-2017-004794_EN.html (accessed on 29 November 2020).

58. SEP. Science for Environment Policy (2016) No Net Land Take by 2050? Future Brief Produced for the European Commission DG Environment by the Science Communication Unit, UWE, Bristol. 2016. Available online: http://ec.europa.eu/science-environment-policy (accessed on 16 May 2018).

59. Siscan, Z.; Kaim, M. Green In Proceedings of Entrepreneurship in the Republic of Moldova and European Circular Economy Trend. Presented at Conferinţei Ştiinţifice Internaţionale, Ediţia a XXII-a, 2020, Chişinău, ASEM, Moldova, 25–26 September 2020.

60. Hoang, N.T.; Kanemoto, K. Mapping the Deforestation Footprint of Nations Reveals Growing Threat to Tropical Forests. Nat. Ecol. Evol. 2021.

61. Benton, T.G.; Bieg, C.; Harwatt, H.; Pudasaini, R.; Wellesley, L. Food System Impacts on Biodiversity Loss. 2021. Available online: https://www.chathamhouse.org/sites/default/files/2021-02/2021-02-03-food-system-biodiversity-loss-benton-et-al_0.pdf (accessed on 30 March 2021).

62. Bar-On, Y.M.; Phillips, R.; Milo, R. The Biomass Distribution on Earth. Proc. Natl. Acad. Sci. USA 2018, 115, 6506–6511.

63. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. Science 2019, 360, 987–992.

64. EC. New Consumer Agenda—Strengthening Consumer Resilience for Sustainable Recovery. Volume COM(2020) 696 Final. 2020. Available online: https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2020)696&lang=en (accessed on 20 January 2021).

65. EC. Farm to Fork Strategy—For a Fair, Healthy and Environmentally-Friendly Food System. 2020. Available online: https://ec.europa.eu/food/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf (accessed on 20 February 2021).

66. Chemnitz, C.; Wenz, K. Fleischatlas 2021—Daten und Fakten über Tiere als Nahrungsmittel. Auflage, Januar 2021 ed. Heinrich-Böll-Stiftung, Bund für Umwelt und Naturschutz Deutschland & Le Monde Diplomatique. 2021. Available online: https://www.boell.de/sites/default/files/2021-01/Fleischatlas2021_0.pdf (accessed on 8 January 2021).

67. Macleod, M.J.; Hasan, M.R.; Robb, D.H.F.; Mamun-Ur-Rashid, M. Quantifying Greenhouse Gas Emissions from Global Aquaculture. Sci. Rep. 2020, 10, 1–8.

68. Brüggmann, A.; Gebauer, R.; Kloas, W. Towards Developement of Sustainable Aquaponic Fish Feed: Effect of Fish, Insect, Blood and Feather Meal Based Diets on Nutrients in RAS with Colossoma Macropomum. 2019. Available online: https://www.researchgate.net/publication/336651324_TOWARDS_DEVELOPMENT_OF_SUSTAINABLE_AQUAPONIC_FISH_FEED_EFF_INSECT-_BLOOD-_AND_FEATHER-_MEAL_BASED_DIETS_ON_NUTRIENTS_IN_RAS_WITH_COLOSSOMA_MACROPOMUM (accessed on 8 January 2021).

69. EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA); Turck, D.; Castenmiller, J.; Henauw, S.D.; Hirsch-Ernst, K.I.; Kearney, J.; Maciuk, A.; Mangelsdorf, I.; McArdle, H.J.; Naska, A.; et al. Safety of Dried Yellow Mealworm (Tenebrio Molitor Larva) as a Novel Food Pursuant to Regulation (EU) 2015. EFSA J. 2021, 19, e06343.

70. Zech, K.M.; Schneider, U.A. Carbon Leakage and Limited Efficiency of Greenhouse Gas Taxes on Food Products. J. Clean. Prod. 2019, 213, 99–103.

71. IPCC. Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. 2019. Available online: https://www.ipcc.ch/site/assets/uploads/sites/4/2021/02/210202-IPCCJ7230-SRCCL-Complete-BOOK-HRES.pdf (accessed on 2 May 2021).

72. Herforth, A.; Ahmed, S. The Food Environment, its Effects on Dietary Consumption, and Potential for Measurement Within Agriculture-Nutrition Interventions. Food Secur. 2015, 7, 505–520.

73. McGill, S.M. 'Peak' Phosphorus? The Implications of Phosphate Scarcity for Sustainable Investors. J. Sustain. Financ. Invest. 2012, 2, 222–239.

74. Schachtman, D.P.; Reid, R.J.; Ayling, S.M. Phosphorus Uptake by Plants: From Soil to Cell. Plant Physiol. 1998, 116, 447–453.

75. Steffen, W.; Richardson, K.; Rockstrom, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; Vries, W.d.; Wit, C.A.d.; et al. Planetary Boundaries: Guiding Human Development on a Changing Planet. Science 2015, 347, 1259855.

76. Elser, J. Phosphorus: A Limiting Nutrient for Humanity? Curr. Opin. Biotechnol. 2012, 23, 833–838.

77. Falkowski, P. The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System. Science 2000, 290, 291–296.

78. Weikard, H.-P. Phosphorus Recycling and Food Security in the Long Run: A Conceptual Modelling Approach. Food Secur. 2016, 8, 405–414.

79. European Parliament. DECISION No 1386/2013/EU—General Union Environment Action Programme to 2020 'Living Well, within the Limits of our Planet'; Official Journal of the European Union: Brussels, Belgium, 2013; Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013D1386&from=EN (accessed on 8 March 2019).

80. Neori, A.; Krom, M.D.; Rijn, J.v. Biogeochemical Processes in Intensive Zero-Effluent Marine Fish Culture with Recirculating Aerobic and Anaerobic Biofilters. J. Exp. Mar. Biol. Ecol. 2007, 349, 235–247.

81. Barak, Y.; van Rijn, J. Biological Phosphate Removal in a Prototype Recirculating Aquaculture Treatment System. Aquac. Eng. 2000, 22, 121–136.
82. Monsees, H.; Keitel, J.; Paul, M.; Kloas, W.; Wuertz, S. Potential of Aquacultural Sludge Treatment for Aquaponics: Evaluation of Nutrient Mobilization under Aerobic and Anaerobic Conditions. Aquac. Environ. Interact. 2017, 9, 9–18.
83. Hua, K.; Bureau, D.P. Modelling Digestible Phosphorus Content Of Salmonid Fish Feeds. Aquaculture 2006, 254, 455–465.
84. Beckers, S. Aquaponics: A Positive Impact Circular Economy Approach to Feeding Cities. Field Actions Sci. Rep. 2019. Special Issue 20. pp. 78–84. Available online: https://journals.openedition.org/factsreports/5757 (accessed on 8 March 2021).
85. Weidema, B. Market Information in Life Cycle Assessment. 2003. Available online: https://lca-net.com/files/Market-information-in-life-cycle-assessment.pdf (accessed on 15 November 2018).
86. Langergraber, G.; Castellar, J.A.C.; Pucher, B.; Baganz, G.; Milosevic, D.; Andreucci, M.B. A Framework for Addressing Circularity Challenges in Cities with Nature-based Solutions. Water 2021. submitted.
87. Hoelscher, M.-T.; Nehls, T.; Jänicke, B.; Wessolek, G. Quantifying Cooling Effects of Facade Greening: Shading, Transpiration and Insulation. Energy Build. 2016, 114, 283–290.
88. Hoffmann, K.A.; Šuklje, T.; Kozamernik, J.; Nehls, T. Modelling the Cooling Energy Saving Potential of Facade Greening in Summer for a Set of Building Typologies in Mid-Latitudes. Energy Build. 2021, 238, 110816.
89. Saad, R.; Hoffmann, K.A.; Paton, E.; Nehls, T. Modelling the Water Demand of Urban Vertical Green—Verticalizing the Standard Evapotranspiration. Hydrol. Earth Syst. Sci. 2021. Unpublished work.
90. Kloas, W.; Groß, R.; Baganz, D.; Graupner, J.; Monsees, H.; Schmidt, U.; Staaks, G.; Suhl, J.; Tschirner, M.; Wittstock, B.; et al. A New Concept for Aquaponic Systems to Improve Sustainability, Increase Productivity and Reduce Environmental Impacts. Aquac. Environ. Interact. 2015, 7, 179–192.
91. Möller, K.; Burgschweiger, J. Wasserversorgungskonzept für Berlin und für das von den BWB versorgte Umland. 2008. Available online: https://digital.zlb.de/viewer/resolver?urn=urn:nbn:de:kobv:109-opus-133719 (accessed on 26 August 2018).
92. BLN. BLN reicht Unterlassungsklage zum Berliner Moorschutz ein. Berliner Landesarbeitsgemeinschaft Naturschutz e.V. Available online: https://www.bund-berlin.de/service/meldungen/detail/news/bln-reicht-unterlassungsklage-zum-berliner-moorschutz-ein/ (accessed on 28 April 2021).
93. SenUVK. Erarbeitung Masterplan Wasser—Berlin. Senate Department for the Environment, Transport and Climate Protection. Available online: https://www.berlin.de/sen/uvk/umwelt/wasser-und-geologie/masterplan-wasser/ (accessed on 28 April 2021).
94. Cuce, E.; Harjunowibowo, D.; Cuce, P.M. Renewable and Sustainable Energy Saving Strategies for Greenhouse Systems: A Comprehensive Review. Renew. Sustain. Energy Rev. 2016, 64, 34–59.
95. Hemming, S.; Balendonck, J.; Dieleman, J.A.; de Gelder, A.; Kempkes, F.L.K.; Swinkels, G.L.A.M.; de Visser, P.H.B.; de Zwart, H.F. Innovations in Greenhouse Systems—Energy Conservation by System Design, Sensors and Decision Support Systems. Acta Hortic. 2017, 1–16.
96. Opdam, J.J.G.; Schoonderbeek, G.G.; Heller, E.M.B.; De Gelder, A. Closed Greenhouse: A Starting Point for Sustainable Entrepreneurship in Horticulture. Acta Hortic. 2005, 691, 517–524.
97. Körner, O. Models, Sensors and Decision Support Systems in Greenhouse Cultivation. Achiev. Sustain. Greenh. Cultiv. 2019, 379–412.
98. Williams, A. Mythical Food Miles? Planet Earth 2013, 18–19. Available online: https://issuu.com/nerc/docs/pe_spring_13/18 (accessed on 28 June 2019).
99. Payen, S.; Basset-Mens, C.; Perret, S. LCA of Local and Imported Tomato: An Energy and Water Trade-Off. J. Clean. Prod. 2014, 87.
100. Sommer, F.; Dietze, V.; Baum, A.; Sauer, J.; Gilge, S.; Maschowski, C.; Gieré, R. Tire Abrasion as a Major Source of Microplastics in the Environment. Aerosol Air Qual. Res. 2018, 18, 2014–2028.
101. Evangeliou, N.; Grythe, H.; Klimont, Z.; Heyes, C.; Eckhardt, S.; Lopez-Aparicio, S.; Stohl, A. Atmospheric Transport is a Major Pathway of Microplastics to Remote Regions. Nat. Commun. 2020, 11.