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City or hinterland – site potentials for upscaled aquaponics in a Berlin case study

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Sustainably feeding the rapidly growing urban populations requires resource-efficient food production solutions, such as aquaponics. To assess its upscaled fruition in city regions, we applied system analysis to depict determinants of aquaponics at a mesoscale. Using Berlin as a case study, site potentials regarding the production of freshwater fish, tomatoes, and lettuce to achieve self-sufficiency were investigated. We analysed planning documents by text mining and applied geographic information system procedures to evaluate this technology's spatial efficacy in intra- and peri-urban spaces, considering aspects of economy, sustainability and spatial distribution. In a facility-based approach, we contrasted specific intra- and peri-urban site potentials with their different boundary conditions. A thereupon-based scenario allocates approximately 20% of the production volume in Berlin, 80% in its hinterland, and emphasises the crucial use of circular economy resources in both spaces. Policy recommendations and the transferability of this realistic approach will support the implementation of aquaponics.

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INTRODUCTION

Humans can completely destroy their livelihoods, so necessary transformations should not be postponed because the globally disadvantaged will vigorously seek and find access to the Western world's life models and standards[1]. In the 25 years since this was stated, e.g. per capita meat consumption has risen much faster in developing countries than in developed[2,3] due to the West's poor role model – with all collateral negative environmental impacts[4,5]. The IPCC[6] estimated that current global food systems, including pre- and post-production, account for 21–37% of total net anthropogenic greenhouse gas (GHG) emissions. Food systems are accelerating the climate crisis due to the near-linear relationship between cumulative GHG emissions and global surface temperature increase[7]. The European Court of Auditors reports that emissions from livestock, which account for half of the GHG emissions from agriculture in the EU, did not decrease between 2010 and 2018[8]. Capture fisheries cannot be an alternative to livestock farming, as they have been reaching their limits for years, but aquaculture provides great potential – being the primary source of fish for human consumption since 2016[9], with low GHG emissions compared to terrestrial livestock[10]. Nota bene: fishing in cities could be a slight supplement[11].

Urbanisation is an accelerating aspect of the Anthropocene[12], and thus cities are in the focus of transformation towards sustainability[13,14], to 'meet the needs of the present without compromising the ability of future generations to meet their own needs'[15] with respect to social, economic and environmental conditions[16]. Urban food practices are one key lever therein[17], supporting the UN sustainable development goals SDG 3 'Ensure healthy lives and promote well-being for all at all ages', SDG 11 'make cities and human settlements inclusive, safe, resilient and sustainable', and SDG 12 'ensure sustainable consumption and production patterns'[18]. The Milan Urban Food Policy Pact states that accelerating urbanisation requires a re-examination of how cities are provisioned with food[19]; the New Leipzig Charta explicitly identifies local and regional food systems to achieve sustainable and resilient urban development[20,21]. Food has been added to the priority themes of the Urban Agenda for the EU[22], and ensuring sustainable food production is a central element of the EU's Farm to Fork Strategy[23]. Food and biomass production is a challenge concerning the shift to circular city management of resources[24], and closing loops of urban agricultural input and output streams supports these processes[25,26]. Resilience is considered an inherent trait of urban agriculture[27] and peri-urban food production[28].

Circularity is inherent in the aquaponic principle, where water from aquaculture (e.g. fish) is used for plant nutrition and irrigation (e.g. vegetables). This principle is utilised in resource-efficient application fields: whilst aquaponics is restricted to aquaculture in tanks and plant cultivation in hydroponics, trans-aquaponics applies the aquaponic principle without these restrictions – aquaponic farming encompasses both as an umbrella term[29]. Aquaponics can contribute to sustainability[29,30], urban food sovereignty[31] and, according to the German aquaculture strategy, may increase regional self-sufficiency[32]. Urban planning tools and their impacts[33] determine, among other boundary conditions, the spatial distribution of aquaponic farming within a city and its region.

The production of vegetables in a city like Berlin through aquaponics could significantly reduce environmental impacts[30]. Expanding aquaponics to a scale that meets the demand in aquaponically produced food requires a production shift from other locations to Berlin[34]. Studies exist that have explored the potential of urban agriculture in Berlin[35–37], and rooftops have been proposed as a location. In addition, a practice guide for rooftop greenhouses was developed[38]. The city's roofscape offers space, but as on the ground, there are competing uses, which raises the question whether the calculated potential for urban agriculture, including aquaponics can be fully realised[39]. Focusing on the intra-urban areas is important for using circular city

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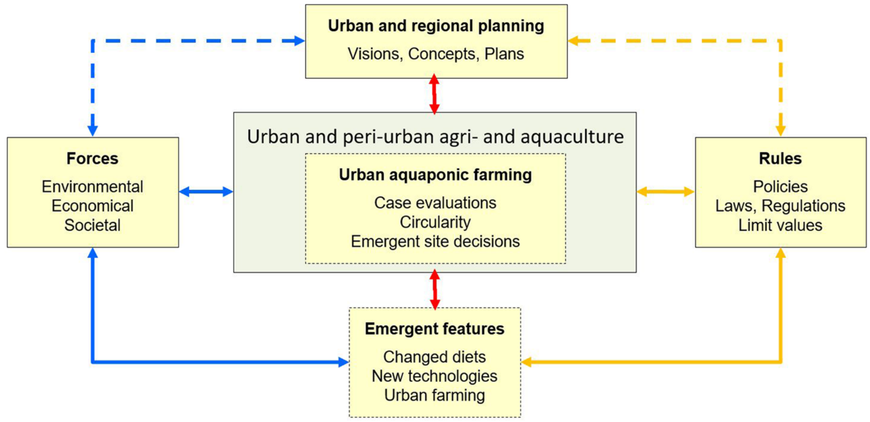

Fig. 1 Determinants of aquaponic farming in city regions. System of determinants of aquaponic farming as part of urban and peri-urban agri- and aquaculture (simplified), adopted from Baganz et al.[33]; arrows in both directions indicate mutual causal relations, dashed lines indicate rather indirect effects, arrow colours indicate group relations; CC-BY 4.0 Gösta F.M. Baganz.

resources[40], but the self-sufficiency of a metropolitan region relies on a foodshed that goes beyond[41]. Thus, both Berlin and its hinterland (Berlin/hinterland) should be research subjects.

The investigation of site potentials for the spatial distribution of facilities to realise the production volume in an upscaled aquaponic scenario includes the following research topics: (1) Key determinants for aquaponic farming in a city region, (2) Role of urban farming and aquaponics in Berlin's urban development strategies, (3) Identification of candidate buildings in intra-urban areas allowing aquaponic integration, (4) Prerequisites for sustainable peri-urban aquaponics, and (5) Development of a Berlin/hinterland scenario for self-sufficiency regarding aquaponic products.

The overall objective of this study is to find site potentials for aquaponics at a mesoscale, identify respective boundary conditions, and derive policy recommendations. Furthermore, we consider sustainable, economic, legal, and settlement structure aspects as well as discuss the transferability of the results to other metropolitan areas. Details of concrete sites, investment costs, funding conditions and workforce requirements are not considered.

RESULTS AND DISCUSSION

Determinants of aquaponic farming in a city region

Prior to discussing the issue of siting – city or hinterland – we depict environmental, socioeconomic, cultural, and policy factors which determine aquaponics and trans-aquaponics (i.e. aquaponic farming) in a city region from the point of view of system analytics (cf. Fig. 1). This approach highlights the overall context before dealing in detail with the intra- and peri-urban spaces.

Forces such as local climate (radiation and average temperature in the cold season) and climate change, land usage competition and prices, labour costs, and societal conditions for aquaponics are one domain determining the transposition of aquaponic farming. Rules at different levels are another important domain: construction laws, building permits, and operating regulations depend on various national and local legal conditions, which often involve a variety of applicable laws, regulations, and exceptions[42]. For example, aquaponics exploits hydroponics and is therefore excluded from organic certification in the EU[43]. However, organic aquaponic farming is possible through trans-aquaponics, which instead includes soil-based plant cultivation methods[29]. Driven by the forces and rules, features emerge from bottom-up processes, often related to market mechanisms (e.g. new technologies, urban farming) or social change (e.g. urban gardening, dietary behaviour) as a mixture of recent phenomena and old features (e.g. urban farming in Berlin is an agricultural heritage[44]). Urban and regional planning seeks to shape land use and the built environment in participatory top-down processes through visions, concepts, plans, and other instruments (cf. Fig. 1). Aquaponic farming is implemented by stakeholders who perform case evaluations by pondering their options (e.g. through SWOT-[25] and profitability analysis[45]). Circularity should play a role: for example, in Berlin, a model facility needs circular city energy resources to reduce its environmental footprint compared to the current German market mix of consumed tomatoes and lettuce of different origins[30]. Sites within a city region are connected to the resources of the circular economy or circular city to varying degrees[40,46] (cf. Fig. 3). Site selection decisions are part of the above-mentioned emergent bottom-up processes.

Berlin's spatial policies

Berlin's population grew by 245,000 from 2011 to 2016 and is projected to increase by an additional 180,000 inhabitants from 2017 to 2030[47]. Local authorities have developed the Berlin Strategy 2030[48] and are constantly evolving spatial plans at the city-wide level, such as the land use plan (zoning plan, FNP[49]), various urban development plans (StEP), and the landscape programme (LaPro[50]). The city administration is working on a participatory Berlin food strategy[51]. On the other hand, there are bottom-up initiatives, e.g. on urban gardening[52–54]. In the coming years, the Berlin municipality will develop 16 new urban quarters with almost 52,000 flats[55]. Urban development concepts exist for these quarters, e.g. the charter for the Kurt-Schumacher-Quartier in Tegel[56] or a draft for Blankenburger Süden as a circular organised neighbourhood[57]. At best, these concepts include urban gardening but not urban farming. Moreover, currently existing agricultural land will be used (1) as building land for some of the new quarters and (2) for ecological compensation for the impact on nature caused by implementing new neighbourhoods.

We performed an analysis of 51 documents on city, sector, and neighbourhood levels to capture the role of urban agriculture in Berlin's spatial planning. As our focus was on aquaponics, we considered community gardens but excluded allotment gardens due to their small and private nature. We have also examined the production side of nutrition in this context – the consumption side (retail markets) was excluded. This investigation revealed that commercial urban farming is currently of secondary importance in Berlin's planning. Urban farming is seen in its traditional context and not as a promising opportunity for a circular city, while urban gardening is featured in some plans. The Berlin food strategy also highlights urban gardening in terms of social effects[51,58], as does the London food strategy[59].

Table 1. Frequency of bigrams containing agriculture, garden or nutrition with at least two mentions in a corpus of selected Berlin spatial planning documents.

Sub-corpus: scope of spatial planning Corpus: 41,057 meaningful words	Document count In sub-corpus	Agriculture[a]	Garden[a] Excluding allotment gardens	Nutrition[a] Excluding markets
City as a whole	8	16 (5)[b]	1 (1)	0 (0)
Sectoral urban development plans	7	4 (2)	15 (3)	0 (0)
Exposés concerning new urban quarters	16	7 (3)	2 (2)	0 (0)
Studies concerning new urban quarters	20	8 (2)	30 (5)	4 (2)
Total	51	35 (12)	48 (11)	4 (2)

[a]Number of bigrams (containing a key word) with at least two appearances in the corpus.
[b]Values in brackets: number of related documents.

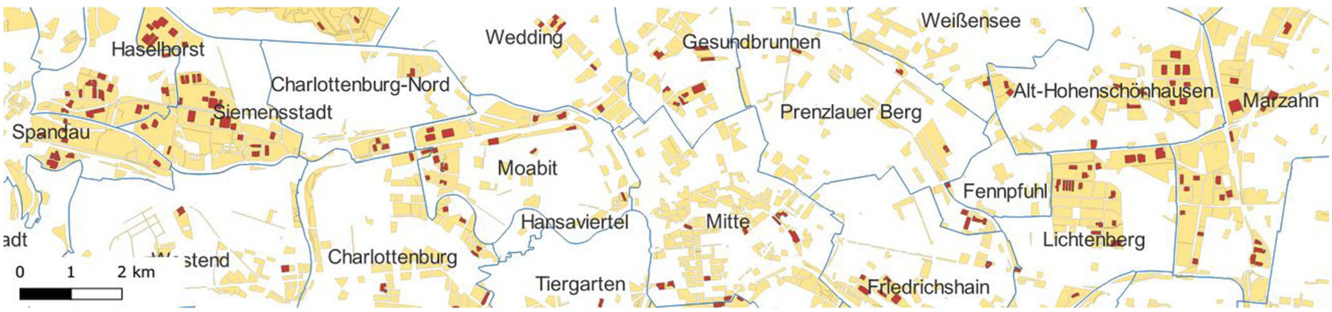

Fig. 2 Candidates for building-integrated aquaponics. Section of candidate buildings in Berlin (red) within urban structure types appropriate for aquaponic sites (yellow); city district names (black); CC-BY 4.0 Gösta F.M. Baganz/dl-de/by-2-0 Geoportal Berlin [ALKIS Berlin Ortsteil, Bauwerke]/Umweltatlas Berlin [Stadtstruktur 2015].

In order to substantiate these results quantitatively, a text mining procedure was applied to form the documents into a corpus. Relevant bigrams (two adjacent words) with an agricultural context based on agricultural keywords were selected in a document-feature matrix (cf. Table 1).

The corpus of 51 documents counted 41,057 meaningful words as the basis for only 35 'agriculture'-, 48 'garden'-, and 4 'nutrition'-bigrams. The corpus did not contain 'urban agriculture', 'urban farming', or 'aquaponics'. For comparison, the most frequent tokens were Berlin (3311), city (1546) and area (1031). Regardless of the low importance of urban farming in Berlin's spatial planning, aquaponics can already be implemented as an emergent feature, e.g. in commercial or urban area[60] zones.

Potential sites of intra-urban aquaponics

An upscaled aquaponic scenario for Berlin was a key result from Baganz, et al.[34], showing that complete coverage of the demand for freshwater fish, tomatoes, and lettuce is possible. Four facility types were modelled[34] with different relative plant yields, i.e. the plant yield per kg fish. Fish and vegetable production was balanced across all facility types[34]. This intra-urban scenario needs 370 facilities of 6050 m^2 each, occupying a total area of 224 hectares (ha)[34]. Suitable urban sites would be required for these commercial urban aquaponic facilities. As carriers of ecosystem services, green spaces should not be treated as land reserves. Therefore, intra-urban aquaponic systems should be building-integrated, i.e. inside or on the roof. Using the geographic information system (GIS) approach presented in the Methods section, 484 candidate buildings with compact floor plans greater than 6050 m^2 and a total area of 554.9 ha were identified within urban structural types appropriate for aquaponics (excluding, e.g. residential use). Figure 2 shows a subset of the result, and Supplementary Fig. 1 highlights the compact floor plans.

Buildings with unsuitable function (e.g. underground garages) were excluded. The remaining buildings offer potential on flat roofs and top floor ceilings on pitched roofs[61]. The structural fitness of buildings was not assessed, but a study[35] demonstrated a roof reinforcement solution for aquaponics.

Building-integrated aquaponics is not restricted to rooftops. The aquaculture subsystem could be integrated into the interior of a building, e.g. in a former malt factory (cf. Supplementary Fig. 2). Interior solutions would prevent or reduce static problems.

206 of the 484 candidate buildings had a promising building function and no more than four storeys (cf. Table 2). These buildings could be ranked by the amount of effort required to make necessary modifications to integrate aquaponics or trans-aquaponics. Assuming that the effort to do so[62] is manageable for the top third, this would represent about 14% of all candidate buildings.

A detailed assessment of the candidate buildings and newly planned buildings for potential aquaponic uses was beyond the scope of this study. Multifunctionality is a trait of cities. Even if all building candidates could be (partly) repurposed, it can be suspected that other urban uses besides aquaponics would come into play. However, aquaponics is an emergent feature (cf. Fig. 1), and location decisions involve many factors outside these considerations.

Boundary conditions of peri-urban aquaponics

Considering the hinterland of Berlin as space for aquaponic facilities allows for significantly larger greenhouses than in intra-urban areas, so economies of scale take effect. The peri-urban scenario also needs 224 ha[34], equal to 16 peri-urban aquaponics with 14 ha each (cf. "Methods" section). Concomitantly, this leads to a conflict of objectives with three goals of intra-urban aquaponics: (1) reducing the environmental footprint through circular city resources, (2) reducing net land take, and (3) reducing transportation impact. In the following, we present options to address this trade-off.

Table 2. Buildings with promising functions to integrate aquaponics or trans-aquaponics.

Code	Building function	Count[a]	Number of floors	Floor plan [m²]	Compactness[b]
			Avg	Avg	Avg
2111	Factory	128	2.3	11139	0.59
2052	Shopping centre	28	2.8	12097	0.51
2054	Store	28	2.2	11017	0.54
2050	Commercial building	15	2.2	11394	0.55
2010	Trade and services building	6	2.0	10442	0.57
2141	Cold storage	1	3.0	7063	0.65
	Total	206			

[a]Buildings up to four floors, > 6050 m^2.
[b]Polsby-Popper-Score.

(1) Reducing the environmental footprint through the circular economy (CE)[63,64] is ruled out at many peri-urban sites due to missing circular economy resource streams. There are exceptions, e.g. a 15-hectare greenhouse using excess heat from agrochemicals production in Piesteritz[65]. The source of energy streams should also be sustainable and not carbon-based, as in Bogatynia, Poland, where a 10-hectare greenhouse[66] is supplied with heat from a coal-fired power plant that emitted 5.5 Mt of CO_2 a^{-1} in 2019[67]. Another example, one of the largest greenhouse operations in Europe, located in Emsbüren, is completely self-supplied with electricity and heat by a combined heat and power plant using wood from landscape conservation. Further CE resources could be heat recovery from wastewater[68] or vegetable waste from aquaponics as an input stream of a biogas plant[69]. Thermal energy is of paramount importance for year-round vegetable production in the Berlin climate with its cold season, and sustainable heating could be provided by excess heat from cooling[30] or by air-source heat pumps. Most heat pumps need electricity, which semi-transparent PV modules could generate on greenhouses. However, studies investigating these modules indicate that they can affect plant growth by reducing light[70–72]. Using solar energy accumulated in summer could be a fundamental solution in winter. Suggestions to solve this problem include decentralised solutions, e.g. greenhouse with thermal storage[73], and long-term storage of gas and electricity within the EU energy grid infrastructure[74,75]. Hydrogen, currently rather expensive, can be produced sustainably and generate both heat and electricity[76] and the German national hydrogen strategy includes storage of hydrogen[77]. In terms of sustainably generated energy and despite potential storage losses, peri-urban greenhouses can be heated sustainably even without access to circular city heat resources.

(2) Reducing net land consumption has been a European goal for years[78], but the German Sustainability Report 2021 still reports an increase in settlement and transport area[79]. Large-scale greenhouses would intensify this negative trend. One solution could be to use areas that have already been designated for the development of commercial/industrial zones; there are almost 26,000 ha in the state of Brandenburg. About 26%, i.e. 6750 ha, are still available[80], and Berlin's hinterland accounts for 2008 ha of this commercial/industrial zone potential[81] of which aquaponics would only need 224 ha[34].

(3) Reducing the environmental impact of transport is an important objective of intra-urban aquaponics. Food miles cause not only GHG emissions[82,83] but also particulate emissions[84,85]. However, the distribution of goods by food wholesalers may involve freight distribution centres located on the outskirts of Berlin[86] for both intra- and peri-urban production sites. In this hypothetical case – without direct selling – the intra-urban advantage is diminished as the average distance from peri-urban locations to the centres increases by only 16–79% compared with intra-urban sites (cf. "Methods" section).

Table 3. Comparison of boundary conditions for two upscaled aquaponic scenarios, each covering Berlin's demand for freshwater fish, lettuce and tomatoes on its own (Intra-urban quantities derived from Baganz et al.[34]).

Site criterion		Intra-urban	Peri-urban
Aquaponics	[count]	370	16
Facility size	[hectares]	0.605	14
Total area	[hectares]	223.9	224.0
Preferable sites		Rooftops/interior of buildings	Unused commercial areas
Net land take		Zero	224 hectares
Sustainable energy		CC[a] ressources	Long-term storage/ CE[b] ressources
CC/CE streams requiring spatial proximity		E.g. grey water, excess heat	E.g. excess heat (biogas plant), CO_2
Logistics		Disruptive in sensible districts	Difficult, when away from main traffic links
Network configuration (wholesalers involved)		23 times as many production sites	16–79% longer distances
Adapting structural fitness of existing buildings		E.g. rooftop, floors, cellar etc.	–
Economies of scale		Low	High

[a]Circular city.
[b]Circular economy.

Berlin/hinterland aquaponic self-sufficiency scenario

The Berlin demand for freshwater fish, lettuce, and tomatoes is the starting point for defining a scenario that achieves self-sufficiency in the intra-urban space alone. This approach is also retained for the peri-urban scenario to compare site criteria regarding both scenarios (cf. Table 3).

The criteria show considerable differences for the two areas studied, especially the number of facilities (370 vs 16), net land take (zero vs 224 ha[34]), and economies of scale, which becomes effective particularly with larger greenhouses[87,88]. Critical economic criteria such as investment costs, funding conditions or workforce requirements were not considered. Case studies are available on this topic[45,89].

The intra- and the peri-urban scenarios are not mutually exclusive but a basis for a mixed approach. However, getting an optimised Berlin/hinterland scenario would require a complex calculation going beyond the scope of the present study. Instead, we took 69 buildings, around 14% of all candidate buildings, as the intra-urban potential, leading to an additional need for 13 peri-urban aquaponics to cover the production need. These account for 81.3% of the 223.7 ha of production space required (cf. Table 4). Given the competing urban uses, the intra-urban share of 41.7 ha (18.7%) seems an optimistic assumption but is consistent with the prioritisation of building integration due to land use reduction targets (cf. Introduction section). The scope is different in both areas: while peri-urban facilities focus on food production, intra-urban facilities may additionally support local marketing, social cohesion, and education. Furthermore, there is

Table 4. Berlin/hinterland aquaponic farming scenario.

Criterion		Intra-urban	Peri-urban	Total
Facilities	[count]	69	13	
Facility size	[hectares]	0.605	14.0	
Total area	[hectares]	41.7	182.0	223.7
	Share	18.7%	81.3%	100%
Preferable farming type		Aquaponics	Aquaponics	
	Optional	Trans-aquaponics		
Scope		Food production, marketing, social cohesion, education	Food production	
Site potential utilisation		69 of 484 buildings	182 of 2008 hectares	
	Relative	14.3%	9.1%	

the option to dispense with rooftop greenhouses and use trans-aquaponic solutions with open rooftop fields (which allow organic production[29]).

An essential criterion for the validity of the Berlin/hinterland scenario is the availability of locations. Intra-urban facilities would need 14.3% of the candidate buildings, and peri-urban facilities would require 9.1% of the commercial zone potential. Thus, there is potential for suitable locations in both spaces, but the placement of aquaponics along the urban-rural gradient is highly dependent on the land price.

Spatial efficacy

A 2021 urban development manifesto for Berlin-Brandenburg calls for supporting and expanding sustainable regional food cycles[90]. As a result, this would lead to a city region partnership, which is also supported by the 'Glasgow Food & Climate Declaration'[91,92] and will add to the spatial impact of transformation on the region as solar parks or wind power plants already do.

Berlin is a growing city and strives for sustainable settlement development according to the principle of 'internal before external development'[93]. The roofscape is one option here and in its majority not yet used multi-functionally, but claims are being made of this potential. Berlin has launched subsidy programmes for green roofs, solar panels and rainwater retention, and around 150,000 flats could be created by adding wooden floors to existing buildings[39]. Urban agriculture increases this utilisation pressure by proposing integrating gardens, fields, greenhouses, and aquaponics into the roofscape[38]. A site potential arises from contemporary planning. Aquaponic facilities can be integrated into buildings of new residential quarters, other planned housing locations, and commercial/industrial zones. In Berlin, aquaponics could be part of the productive city, e.g. implemented in 'mixed-use, high density urban areas', which according to § 6a of the building use ordinance[60], permits, among other things, commercial enterprises that do not significantly disturb residential use. This potential of planning was not investigated, as it is not needed to prove the intra-urban scenario.

Moving to the peri-urban with more favourable space conditions for large greenhouses, which benefit from the economies of scale, would significantly alleviate pressure on the intra-urban but lead to the conflict of objectives mentioned above. The EU aims for zero net land take by 2050[94] and thus calls for sustainable land management[95]. At the national level, Germany had set a target to reduce land consumption from about 130 ha d^{-1} in 2002 to 30 ha d^{-1} by 2020[96], but this target was missed and postponed to 2030[97]. The status is measured by the national sustainability indicator 11.1.a[79], according to which the commercial zones in the state Brandenburg are already settlement areas, so setting up aquaponics, there is, statistically speaking, no land consumption. However, these potentials are as yet unused, and the construction of aquaponic facilities would lead to actual land consumption. For example, a commercial zone in the state of Brandenburg had been earmarked for car production for decades - and the eventually implemented factory was an intervention in the natural balance. Especially water bodies[98] and forests were affected, notwithstanding the ecological compensations[99]. Related to aquaponics, peri-urban land consumption can be reduced by using brownfields and/or increasing yield per hectare, e.g. through taller greenhouses (>10 m) or vertical farming technologies.

These considerations could be part of a broader vision to evolve the structure and function of a city region, possibly inspired by Howard's garden city concept, which envisages an intertwined network of urban and rural spaces to achieve self-sufficiency[100]. There is 'Berlin's garden city of the twenty-first century', but its districts are stripped of their supply function and seen as urban building blocks for the inner development of the outer city[101]. They feature community gardens, thus contributing to social cohesion and ecosystem services[102]. Trans-aquaponic applications such as pond aquaponics may be applied, but in contrast to the Berlin/hinterland scenario, this concept does not focus on commercial food production.

The Berlin/hinterland scenario is a simplified and possible solution. Aquaponic farming may pursue different primary goals, such as profitability[45], sustainability[30], social impact (like urban gardening[103,104]), or education (like aquaponics at the FEZ youth centre in Berlin[105]). The present study focuses on sustainability, which can be enhanced by integrating aquaponics into the circular city[46]. Profitability is possible from a facility size of 0.2 ha and direct selling[45]. From the logistics point of view, direct selling farms are best located in intra-urban areas, whereas peri-urban farms are more dependent on wholesalers. Especially in peri-urban areas, different spatial qualities of sites should also be considered regarding transport[106]. No investigations have been carried out regarding transporting and storing of all commodities (input and output) in different scenarios. Nevertheless, whatever a fully-fledged realisation may look like, it will be exemplary for spatial distribution conflicts in the relationship structure of the determinants of aquaponic farming (cf. Fig. 1). The implementation of the scenario will stretch over time and space requirement will increase if: (1) the peri-urban inhabitants are also included because their need of aquaponic products was not considered in the underlying study[34]; (2) freshwater fish would replace saltwater fish because sustainable farmed aquatic foods should focus on freshwater aquaculture[107]; (3) freshwater fish would replace meat in changing diets[41,108]; and (4) the population were to grow.

Another solution would be a 'climate zones advantage scenario'[34] in which only fresh tomatoes would be produced in Berlin in facilities with a winter break for crop production[45], and the import of fresh tomatoes (which consist mainly of water) from southern regions would be restricted to winter. Tomatoes for processing would be produced in the South and exported to Berlin as tomato products. This scenario would require less space in Berlin, but local aquaponics would not be self-sufficient, and the scenario's sustainability would still need to be proven.

Water and embodied CO_2

Agriculture needs to reduce carbon emissions[109], but self-sufficiency does not necessarily mean sustainability. The environmental footprint of the Berlin/hinterland aquaponic scenario should be smaller than the current footprint of the respective food production so that sustainability is valued over self-sufficiency. A causal relation analysis stated that a production-location shift to Berlin would increase the locally embodied CO_2 and the water

Table 5. Mesoscale policy goals (+), constraints (-), and boundary conditions (o) related to aquaponics in a city region.

	Intra-urban aquaponics		Peri-urban alternatives
+	Use of circular city energy resources	o	Sustainable energy supply in cold season, decentralised solutions, grid-based long-term energy storage
+	Zero net land take	-	Net land take, mitigated by: use of brownfield sites, space potential of settlement areas, excluding valuable soils or habitats
o	Low transport impact (direct selling, impact increases if peri-urban logistics are involved)	o	Logistics centres on the city's outskirt reduces intra-urban transport advantages
-	Low economies of scale: reduces income	+	Large greenhouses enable economies of scale
-	Intense competition for use: increases expenditure	+	Existing space potential in commercial/industrial zones

demand for local food production[34]. For precise impact analysis, the CO_2 footprint embodied in the buildings and the technical equipment would need to be considered. Drinking water demand will increase due to the projected population growth in Berlin and its hinterland[110]. At the same time, climate change will lead to a decrease in groundwater recharge, an increase in evaporation losses, and more frequent and prolonged periods of drought. The Berlin Master Plan Water already shows overuse of the groundwater supply of 2%[110]. Upscaling aquaponics would increase the local water demand, regardless of the dual use of water, but would save about 2,050,000 m^3 a^{-1} of water compared to separate fish and plant farming[34].

Transferability to other city regions

Urban aquaponic farming is an emergent feature. Systems are already being implemented, as shown in a literature review[111] and by the 2021 example of a German supermarket with rooftop aquaponics[112]. However, urban aquaponics is not yet a widespread phenomenon – neither globally nor in Germany or Berlin – but it is worth becoming one. The use case Berlin refers to the local conditions prevailing here, i.e. climate conditions, a growing city, green spaces to be preserved, and commercial/industrial zones in its hinterland that are not yet occupied. A city with many urban brownfields, such as Detroit[113] provides enough space for single-storey aquaponics; in a city with limited land in the surrounding area like Rotterdam[41], more building-integrated potential would need to be exploited. Our generalised approach (cf. Methods section) has the necessary flexibility to be applied to other city regions; however, in addition to spatial efficacy, city-specific conditions determine success, as illustrated by the example of urban agriculture in New York[114].

Policy recommendations

We have identified a sufficient number of suitable intra-urban candidate buildings in terms of size, function, and geometry to potentially house aquaponic facilities. There are good reasons in favour of aquaponics in an intra-urban context, such as: (A) the use of circular city energy resources; (B) zero net land take of building-integrated aquaponics; and (C) low transport impact (e.g. with direct selling). On the other hand, there are strong arguments against it: low economies of scale (lower revenues) and intense competition for use (higher expenses). Weighing the disadvantages of intra-urban sites, additional locations in the city's vicinity are to be considered.

The advantages of intra-urban aquaponics should be a role model for using peri-urban space. Options are: (A) sustainable energy supply in the cold season, which could be achieved through decentralised solutions and grid-based long-term energy storage; (B) use of brownfield sites or the existing space potential in commercial/industrial zones, excluding valuable soils or habitats; (C) optimisation of logistics to keep transport impact as low as possible. In a Berlin/hinterland scenario, intra-urban flagship aquaponics in particularly suitable locations could primarily serve marketing and educational purposes, while most production takes place in peri-urban areas.

Infrastructure policies should be informed by approaches on all scales[115]. Our study uses microscale data but addresses the mesoscale of the Berlin city region and its sub-spaces. Urban and regional planning and the rules they set or influence are important determinants of the scope and locations of aquaponics in the city region. The advantages of intra-urban locations can be at least partially transferred to peri-urban spaces, considering that the boundary conditions differ significantly along the urban-rural gradient (cf. Table 5). The further development of aquaponics, such as using insects, duckweed, or algae as fish feed and the closing of material cycles within the facilities, is not considered here.

We conclude these policy recommendations: (1) In the context of urban agriculture, aquaponics and trans-aquaponics should be a topic of Berlin strategies and planning to use circular city resources and make food production visible to citizens. (2) Concerning the overall goals, sustainability should be rated over self-sufficiency. (3) Only aquaponics using sustainable energy should be promoted in the city region, and circular city resources should be encouraged. (4) Zero net land take presumed, intra-urban space should be prioritised. In the peri-urban space, brownfield sites should be rated over unused commercial/industrial zones. (5) In animal protein production, freshwater fish should be preferred over saltwater fish and meat, and this preference should affect corresponding subsidies and be propagated in public nutrition campaigns.

Urban farming, including aquaponics, currently has a low priority in Berlin's spatial planning. Thus, the proposed political recommendations should be reflected in the upcoming Berlin State Sustainability Strategy 2030, which is set out in the coalition agreement for the legislative period 2021-2026[116]. In particular, decisions on selecting aquaponic sites which are part of emergent bottom-up processes should be supported.

METHODS

Determining to-be-built locations

There is a broad theoretical spectrum for determining to-be-built locations. Contributions were provided by Weber[117], who sought to optimise transportation costs, Lynch[118], who focused on urban structural aspects, Batty[119], who attempted to capture the complexity of cities with models, and Alexander[120], who used the 'nature of order' to locate suitable points in the configuration space. Location theories have been operationalised and are available as modern methods of spatial analysis[121] and location modelling[122].

However, the specific locations play a subordinate role in our study because the core of our study is a proposal to answer the city or hinterland question and clarify the related boundary conditions. We held it important to develop an approach that could be applied to other city regions, each with very different local conditions. Thus, we chose a generalised approach: (1) to determine a local target for food production; (2) to examine whether spatial planning strategies support this target; (3) to find two prototypical aquaponic configurations which fit intra- and peri-urban boundary conditions respectively; (4) to build an intra-urban and a peri-urban scenario for comparing the different impact on key criteria; (5) to estimate the number of most promising intra-urban sites; (6) and based on this, to calculate the number of peri-urban facilities required to achieve the food production target. The present approach aims to find a realistic economically and environmentally sound scenario that reflects the emergent bottom-up implementation by facility operators as well as the supporting top-down strategies and planning by local authorities.

Delimitating the intra- and peri-urban

The demarcation between intra- and peri-urban can be made according to functional or administrative criteria. Functionally, being the ambiguous section of the rural-urban continuum[123], the peri-urban can be delineated by urban-rural gradients[124–126] or a city clustering method[127]. Our approach used the administrative regions of the European Union: NUTS[128] and Local Administrative Units (LAU)[129]. We classified the NUTS-1 region Berlin (892 km^2) as an intra-urban and 50 LAU regions around Berlin as peri-urban space. This Berlin hinterland (2863 km^2) is part of the NUTS-1 region Brandenburg (29,654 km^2)[130]. Nota bene: within the administrative intra-urban, the 'immediate surroundings' of urban areas concerning urban agriculture are zero (cf. Supplementary Note 1).

Circular city system boundary

The circular city is a special case of the circular economy[40,46], and the Venn diagram in Fig. 3 shows its relationship with the intra- and peri-urban area. For simplicity, in the present study, we consider the circular city in the intra-urban region and the circular economy in the peri-urban region.

The system boundary of the circular city can also extend into the peri-urban (cf. Fig. 3). A historical example is the Berlin sewage fields, where domestic, commercial and industrial waste waters as well as precipitation water were pumped from intra-urban facilities to peri-urban fields for treatment and agricultural use[44]. The harvests were delivered to the city, completing the circle.

Text analysis of planning documents

To quantify the significance of agriculture in Berlin planning, a selection of planning documents was combined into a corpus on which a computer-assisted text analysis was performed using RStudio 4.0.5 with Quanteda 3.2 and TM 0.7. In the first step, punctuation and stop words were removed from the corpus to keep only meaningful words. A list of German keywords (supplemented by wildcards) with possible agricultural context was defined: *landwirt*, *garten*, *gärten*, *urban*, *agri*, *lebensmittel*, *ernähr*, *nahrung*, fisch*, and aquaponik* (EN: *agri*, *garden*, *urban*, *agri*, *food*, *nutrition*, *nutriment*, fish*, and aquaponics*). To reveal the context of the keywords, word pairs (bigrams) were created by applying this list to the tokens of the corpus. The corpus was then converted into a document-feature matrix, and only bigrams containing words from the keyword list were retained as features in the matrix. To ensure some degree of relevance and to exclude random bigrams, the matrix was reduced to those features (bigrams) that occurred at least twice in all documents. The resulting features were manually checked for an agricultural context, and bigrams without this context were removed from the matrix. Thus, the document-feature matrix contains all documents and only bigrams with an agricultural context. An empty document did not contain any keywords from the beginning or was emptied during processing.

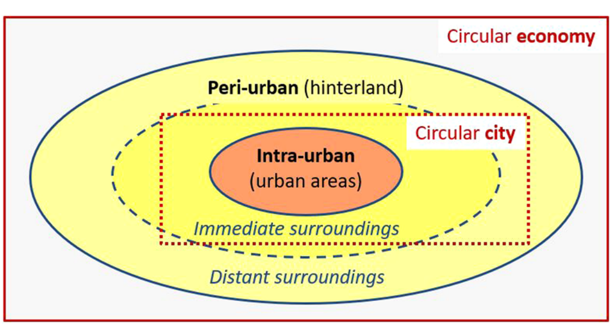

Fig. 3 Local circularity. The circular city and its relationship with intra- and peri-urban areas; CC-BY 4.0 Gösta F.M. Baganz.

Aquaponic model facilities

Aquaponics can be implemented in many forms: from small-scale to large-scale facilities, community-driven or professionally operated. We (1) selected two prototypical model facilities whose size can be considered average for sustainable professional operation in the intra- respective peri-urban area and (2) assumed the distribution of produced commodities by a wholesaler. Both discrete sizes form the basis for calculating a reasonable number of locations. The intra-urban facility is based on an aquaponic model facility used in a life cycle assessment (LCA)[30]. In an upscaling aquaponic scenario for Berlin[34], its size was set to a medium of 0.6 ha, resulting in 370 intra-urban sites. (A case study proposes small 0.12 ha rooftop aquaponics on Berlin residential buildings[62]). The hinterland provides appropriate options for larger aquaponics. A study conducted in Varamin city, Iran, found an optimal tomato greenhouse area regarding economies of scale of 13.8 ha[87]. Examples of similar-sized greenhouses are located not that far from Berlin: a 10 ha greenhouse in Fretzdorf[131], Brandenburg, and a 15 ha greenhouse in Piesteritz[132], Saxony-Anhalt, both about 110 km from the centre of Berlin. We set the size of a peri-urban aquaponics to 14 ha, including aquaculture and plant cultivation. This size is 23 times the size of the intra-urban model facility.

Intra-urban potentials

Building-integrated aquaponics (e.g. rooftop) is preferable to using urban open spaces[39]; thus, the existing building stock was investigated. Berlin building geometries were retrieved from the Official Real Estate Cadastre Information System (ALKIS) via Web Feature Service (WFS)[133] and the geodata were processed using QGIS 3.22. According to the ALKIS object type catalogue[134], the building function was evaluated regarding incompatibility with aquaponic use, e.g. due to an access restriction or waste processing (cf. Supplementary Table 1). The upscaling scenario relies on a facility[30], which uses sunlight (and only supplemental lighting) for plant cultivation; therefore, underground buildings were also classified as unsuitable. The search excluded buildings with floor space < 6050 m^2 and an incompatible building function. Existing or planned roof uses[39] were not taken into account.

Since the effort of installing greenhouses on a building with a fragmented footprint is higher than on a building with a compact footprint, the Polsby-Popper-Score (PPS)[135] was used to measure the footprint compactness. The PPS is calculated as a function of the footprint F:

$$PPS(F) = 4^{*}\pi^{*}A\,P-^{2} \quad (1)$$

with A = area(F), and P = perimeter(F). The result is a value between 0 and 1, indicating the compactness of the building's floor geometry. We chose a PPS value of 0.3 as an empirical

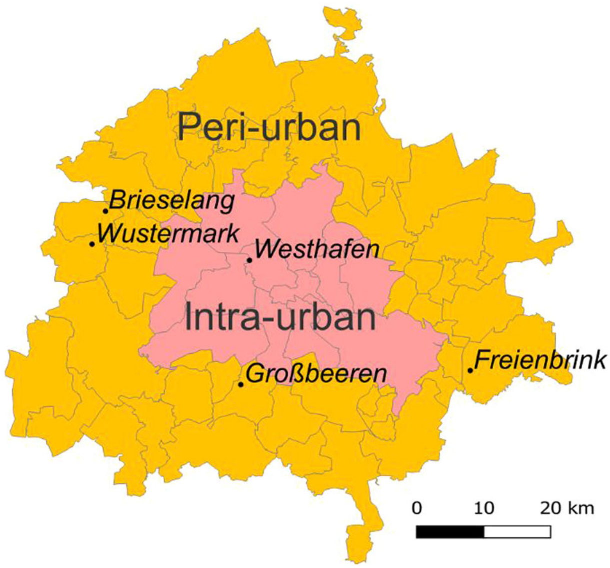

Fig. 4 Berlin's city region. Intra- and peri-urban spaces of the Berlin city region with district borders (grey) and freight distribution centres (italic); CC-BY 4.0 Gösta F.M. Baganz/dl-de/by-2-0 GeoBasis-DE/LGB [WFS BB-BE VG].

threshold and selected all buildings above this score from the result set.

The aim of this search in the context of the city/hinterland issue was to determine whether sufficient buildings of suitable size and shape in appropriate built-up areas are available for the intra-urban aquaponic scenario[34]. Neither the extensibility and convertibility nor the static and legal suitability of the buildings were examined, as not all available intra-urban sites are needed for the Berlin/hinterland scenario (cf. "Results and discussion" section).

To exclude locations where usage conflicts are foreseeable, the concept of urban structural types (USTs) was applied. USTs are an enumeration of types of characteristic built-up structures or land uses. UST has been used for several decades, e.g. in general urban development planning[136]. Besides the UST attribute, Berlin's land use and urban structure mapping units have the attribute 'built-up area usage' (BAU), which enumerates ten different use types[137]. Six of these types were selected as suitable for aquaponic sites (cf. Supplementary Table 2). Inter alia 'residential use' was excluded because of the interfering aquaponic's logistics. The UST data were downloaded from a web feature service available on the Berlin geoportal[138].

The spatial relation of suitable buildings and 'urban structural types' with selected 'built-up area usage' yields potential aquaponic sites. In a further study, this result set could be narrowed down if circular city resources such as greywater or excess heat could be considered. For promising sites, corresponding site resource inventories (SRI)[46] could be compiled; however, city-wide data for SRI is not yet available.

Peri-urban potentials

The Berlin hinterland is part of the federal state of Brandenburg. A monitoring study on commercial/industrial location potential exists[80,81]; therefore, we have omitted a site investigation. In this study, the potential of the commercial zones of a municipality is aggregated and displayed at the centroid of the respective municipality[139]. As aquaponics combines two different production methods, EU countries have implemented differently structured and demanding legal frameworks[140]. In Germany, the 'external area' according to § 35 of the German building code[141] privileges agriculture but not aquaculture, which is a precondition of aquaponics. Most of the hinterland is legally assigned to 'external area'. Commercial/industrial zones in the hinterland simplify permitting aquaponics; therefore, we have searched the planning documents for potentials (cf. "Results and discussion" section) in these zones.

The 12 districts of Berlin form the intra-urban and 50 surrounding Brandenburg municipalities (cf. map 4.1, 'Berliner Umland'[139]) the peri-urban space of the Berlin city region (cf. Fig. 4). In order to estimate the impact when transport is handled via logistics centres, the locations of the five existing logistic centres[142] in the vicinity of Berlin are indicated.

The average distance from each freight distribution centre to the centroids of the districts and municipalities was determined separately for intra- and peri-urban space (cf. Table 6).

The area centroids are taken as a simple model for randomly located producers who distribute their food via peri-urban freight distribution centres. The average distances from the peri-urban producers to these centres are 16% to 79% longer than the average distances from intra-urban producers. This is a moderate increase compared to an intra-urban logistic centre, where the difference is 271%.

Table 6. Average distance from existing freight distribution centres to districts and municipalities (cf. Fig. 4) in the intra- and peri-urban space, with Delta indicating the relative increase in the distance.

Freight distribution centres		Intra-urban[a]	Peri-urban[a]	Delta
Peri-urban	Brieselang	23.3	31.1	133%
	Freienbrink	24.6	28.6	116%
	Großbeeren	12.6	22.5	179%
	Wustermark	23.8	31.3	131%
Intra-urban	Westhafen	5.6	20.8	371%

[a]Average distance to districts [km].

Talks with stakeholders

There are several small aquaponic facilities in Berlin. We visited the facilities ECF Farm (production)[143], Stadtfarm (production)[144], FEZ Berlin (education)[105], Block 6 (abandoned)[35], and IGB (research)[145], where we conducted semi-structured interviews with operators and staff. We also held conversations with investors, policymakers, and researchers. In April 2021, we participated in a Berlin science-practice dialogue on urban and peri-urban food production. The findings from the interviews and talks were used as background information in the present study.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

DATA AVAILABILITY

The datasets generated during and/or analysed during the current study are available in the Zenodo repository[146].

CODE AVAILABILITY

Data processing documentation (workflow and code) and standalone code are available in the Zenodo repository[146].

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