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CITYFOOD: Research Design for an International, Transdisciplinary Collaboration

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Twenty-first-century cities face challenges including potential food shortages, water scarcity, and dependence on nonrenewable energy sources. These are increasingly intensified by global population growth. The development of innovative solutions for the food-water-energy nexus requires transdisciplinary approaches across scales, boundaries, and sectors. The international, interdisciplinary research consortium CITYFOOD investigates the science and practice of aquaponics, an integrated food production system. The three-year research project focuses on the potential for scaling up the integration of aquaponic operations in cities. The team's goal is to expand the knowledge around aquaponics by applying case study research, modeling, and GIS-based mapping methods across various built environment scales. Through projects like CITYFOOD, the growing understanding of interlinkages between food, water, and energy systems can contribute to a more sustainable future.

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Introduction

As global urban populations grow, twenty-first-century cities will have to adapt to complex challenges such as ensuring food, water, and energy security while reducing dependence on nonrenewable resources. Climate change, environmental degradation, and social inequity exacerbate these challenges (Liu et al. 2018). These increasingly pressing problems are interconnected, though they are often studied, managed, and regulated separately. Traditional disciplinary, compartmentalized approaches alone will not solve these problems; integrated, interdisciplinary, and transdisciplinary collaborations that work across scales, boundaries, and sectors toward systems integration are needed (Liu et al. 2015). The food-water-energy (FWE) nexus is one framework that supports this approach; it conceptually connects multiple resource use practices and complex urban infrastructure systems to understand interrelations, potential synergies, and trade-offs (Scott et al. 2015).

The Sustainable Urbanisation Global Initiative/Food-Water-Energy Nexus call, jointly established by the Belmont Forum and Joint Programming Initiative (JPI) Urban Europe in 2016, launched the creation of the international, interdisciplinary research consortium CITYFOOD. The team came together around members' research interest in the science and practice of aquaponics, an integrated food production system with potentially sustainable applications. Aquaponics combines

◁ Figure 1. BIGH's Ferme Abattoir (with an aquaponic greenhouse in the back) built on the roof of the Foodmet market hall (designed by ORG Architecture) in downtown Brussels, Belgium. (Credit: Melvinkobe)

◁ Figure 2. Aquaponic rooftop greenhouse of BIGH's Ferme Abattoir in Brussels, Belgium.

Research Consortium	Research Activities
IGB - Forschungsverbund Berlin e.V. – Leibniz Institute of Freshwater Ecology and Inland Fisheries, Germany	**Aquaponics Knowledge Base (WP1)** Establish a resource repository through an extensive literature review. Develop a taxonomy of terms, and design an interactive website to provide comprehensive knowledge about aquaponic systems to different stakeholders. Lead: UW
GU - University of Gothenburg, Faculty of Science, Department of Marine Sciences, Sweden	**Urban Integration and FWE Nexus (WP2)** Assess the potential for urban integration of aquaponics through a GIS-based parcel and site resource inventory. Identify critical planning criteria for implementation. Study the impacts of urban aquaponics on the FWE nexus. Lead: IGB
NIBIO - Norwegian Institute of Bioeconomy Research Division for Food Production and Society, Norway	**Modeling and Optimization (WP3)** Simulate the environmental, economic, and social performance of aquaponic operations on the system, building, and urban scale. Lead: WU
UNESP - Universidade Estadual Paulista "Júlio de Mesquita Filho," Brazil	**Living Labs, Case Study Research, and Evaluation (WP4)** Assess the practice of aquaponics. Demonstrate the practicability and feasibility of the innovative aquaponic operations to address FWE nexus challenges. Study the performance of commercial farms and evaluate user experiences in living labs. Lead: UNESP
UW - University of Washington, College of Built Environments, USA	**Dissemination and Exploitation (WP5)** Promote the idea of aquaponics to different stakeholders, contribute to environmental education, and stimulate environment-related communication between citizens. Create new market opportunities and jobs. Lead: GU
WU - Wageningen UR, Department of Agrotechnology and Food Sciences, The Netherlands	**Project Coordination and Management (WP6)** Plan, monitor, and control all aspects of the research project. Lead: IGB

◁ Figure 3. Research consortium and primary research activities (WPs).

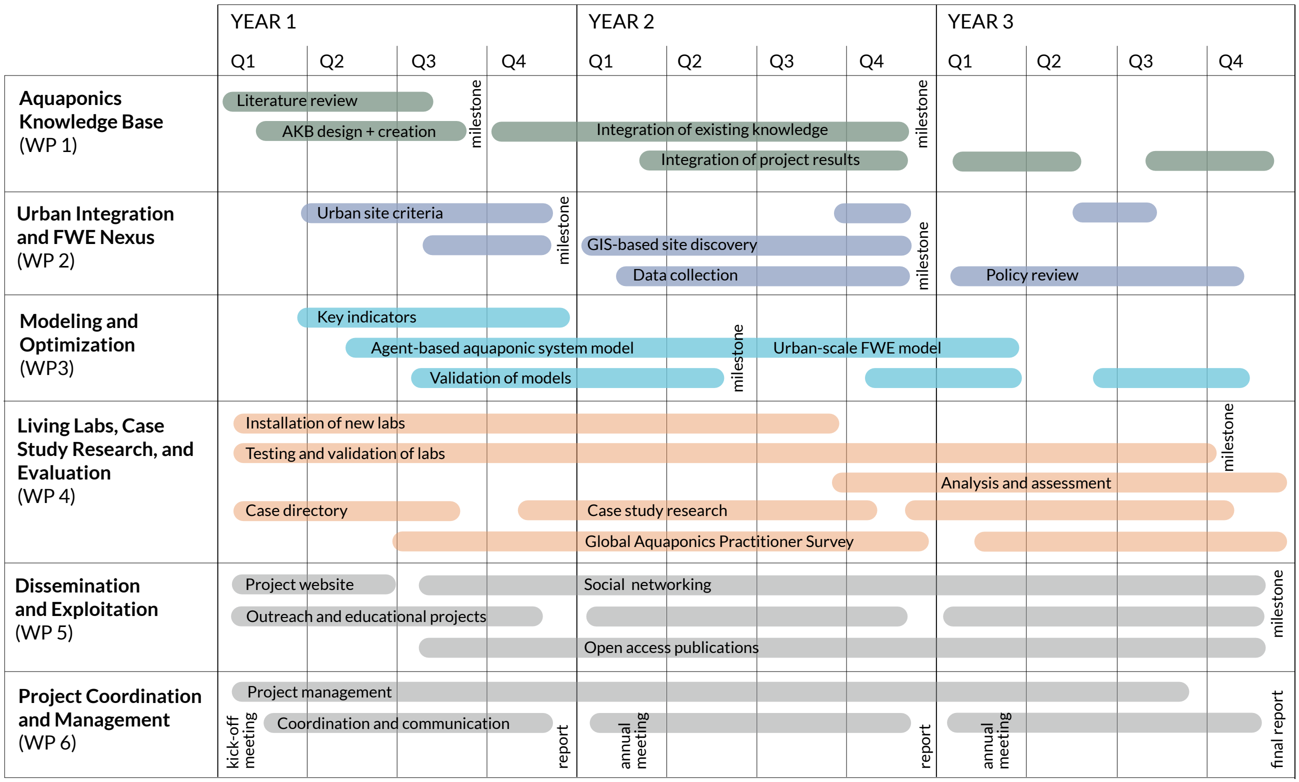
aquaculture and hydroponic cultivation by facilitating nutrient cycling between fish and plants, essentially mimicking the efficiency of a natural ecosystem. In coupled aquaponic systems, water containing fish waste supplies nutrients for crops that then filter the water to a state where it can be returned to the fish tanks safely (Goddek et al. 2015). While the fundamental principle of nutrient exchange has been used by rice-fish farmers in China as far back as the Eastern Han Dynasty (AD 25–220), instances of aquaponic farming have been rare until recently (Kangmin 1988). In the last fifteen years, the contemporary version of aquaponics has experienced a surge in popularity as an emerging sustainable food production strategy (Junge et al. 2017).

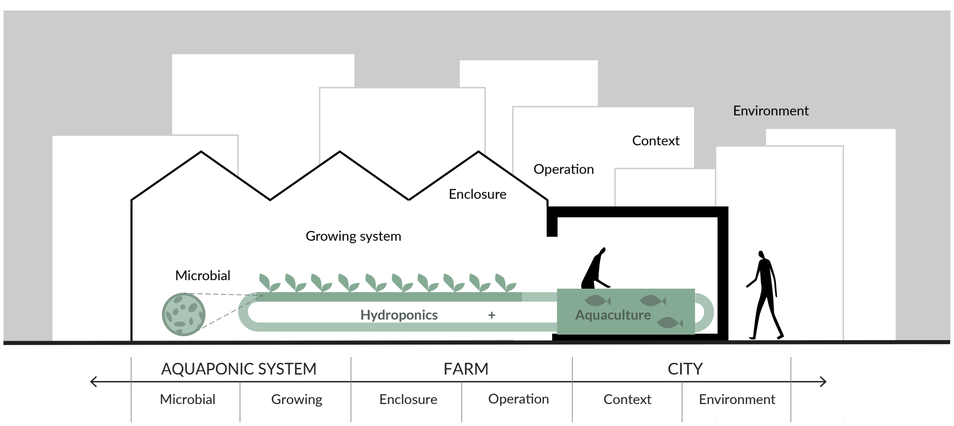
Aquaponics has the potential to provide food for urban residents while creating positive impacts on the FWE nexus, though much of the published research focuses on the aquaponic growing system. The widespread implementation of this technology and its interaction with urban systems has not yet been assessed as only a small number of notable urban operations have been recently implemented (Figures 1 and 2). CITYFOOD investigates the potential for scaling up the environmental, economic, and social integration of aquaponic operations in cities.

Interdisciplinary Expertise Connecting Academia and Practice

The CITYFOOD research consortium consists of six research teams, located in Brazil, the US, and Europe (Germany, Sweden, Norway, and the Netherlands), who bring diverse expertise to the project. Their research interests fall into three broad areas: (1) aquaculture and aquaponics, (2) the built environment, and (3) mathematical and statistical methods. In addition, CITYFOOD's research design integrates a transdisciplinary approach, which generates reciprocal inspiration and collaborations between academia and practice. As a larger trend, recent research shows that teams simultaneously working on foundational and applied research are more likely to achieve significant advances in both areas (Shneiderman 2016). All CITYFOOD research results will eventually be made publicly available in accessible formats for different audiences, such as researchers, practitioners, and other stakeholders via an aquaponic knowledge base (AKB) website.

CITYFOOD Forschungsverbund Berlin e.V. – Leibniz Institute of Freshwater Ecology and Inland Fisheries, Germany (IGB) in Germany led the development of the initial research design. The three-year research project is structured into four extensive, interconnected research activities or work packages (WPs): the evaluation of existing knowledge (WP1), a study of urban





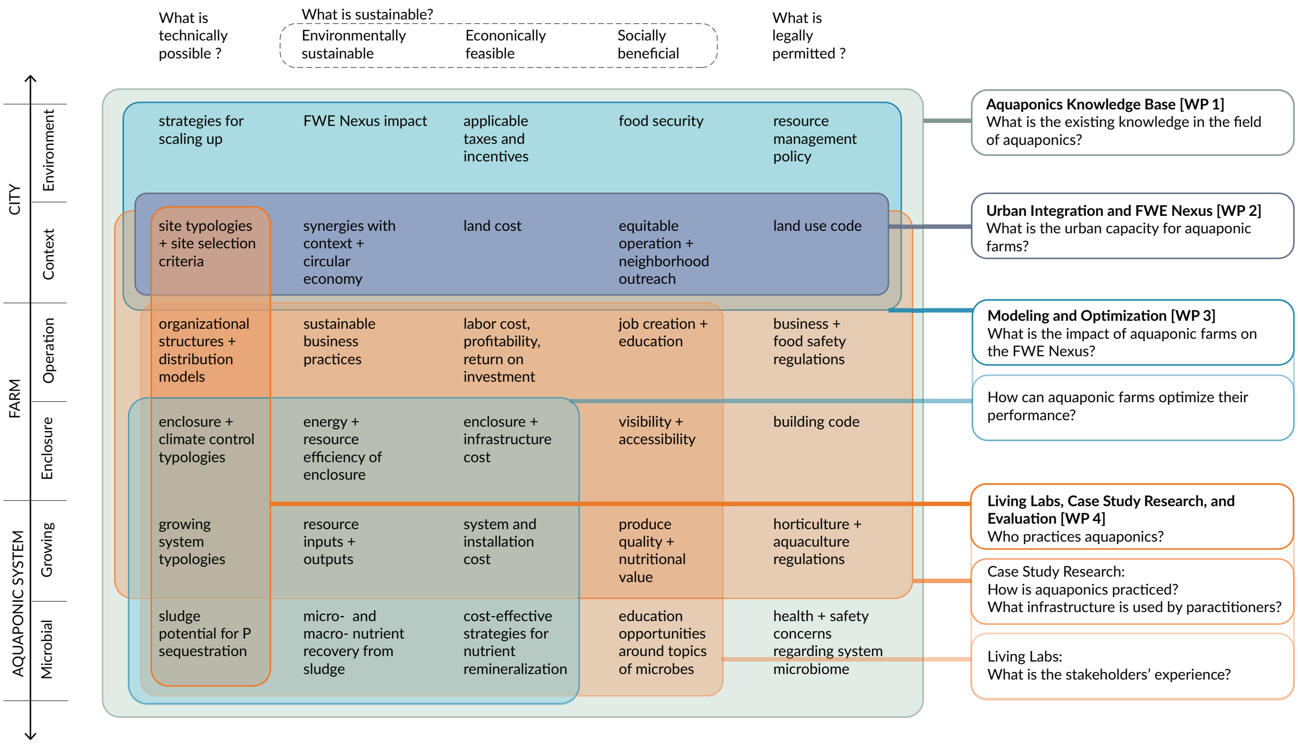
△ Figure 4. Timeline of workflows, milestones, and reporting periods.

◁ Figure 5. Built environment scales relevant to the urban integration of aquaponic farms.

capacity (WP2), modeling of system performance (WP3), and the assessment of the practice of aquaponics (WP4). Two additional WPs improve the workflow through a specific focus on dissemination and outreach (WP5) (CITYFOOD n.d.) and grant management (WP6) (Figure 3). Each national team is primarily responsible for one WP. This leadership includes the coordination of the workflow, methodology, and exchange of data, also guaranteeing that vital deadlines are met (Figure 4). To foster exchange between teams and to provide the necessary overlap of interdisciplinary expertise, multiple teams contribute to each WP. Given the significant physical distance between teams, the communication between six consortium partners on three continents poses a challenge. Accordingly, the consortium has annual meetings, strives to set up additional in-person exchanges, and uses video conference calls to advance the collaboration. In addition to the work within the consortium, each research team collaborates with local partners and stakeholders.

Research Matrix

Based on their respective expertise and work assignments, the various teams started to further refine the research questions and methodologies. The CITYFOOD University of Washington (UW) team in the US interpreted the initial research design from a built environment perspective and integrated relevant scales and implementation criteria into a research matrix. Aquaponic operations work simultaneously on three critical, interdependent scales: (1) the aquaponic system, facilitating the interchange of nutrients between fish and plants; (2) the



△ Figure 6. Research matrix organized by relevant scales and criteria for urban integration of aquaponics.

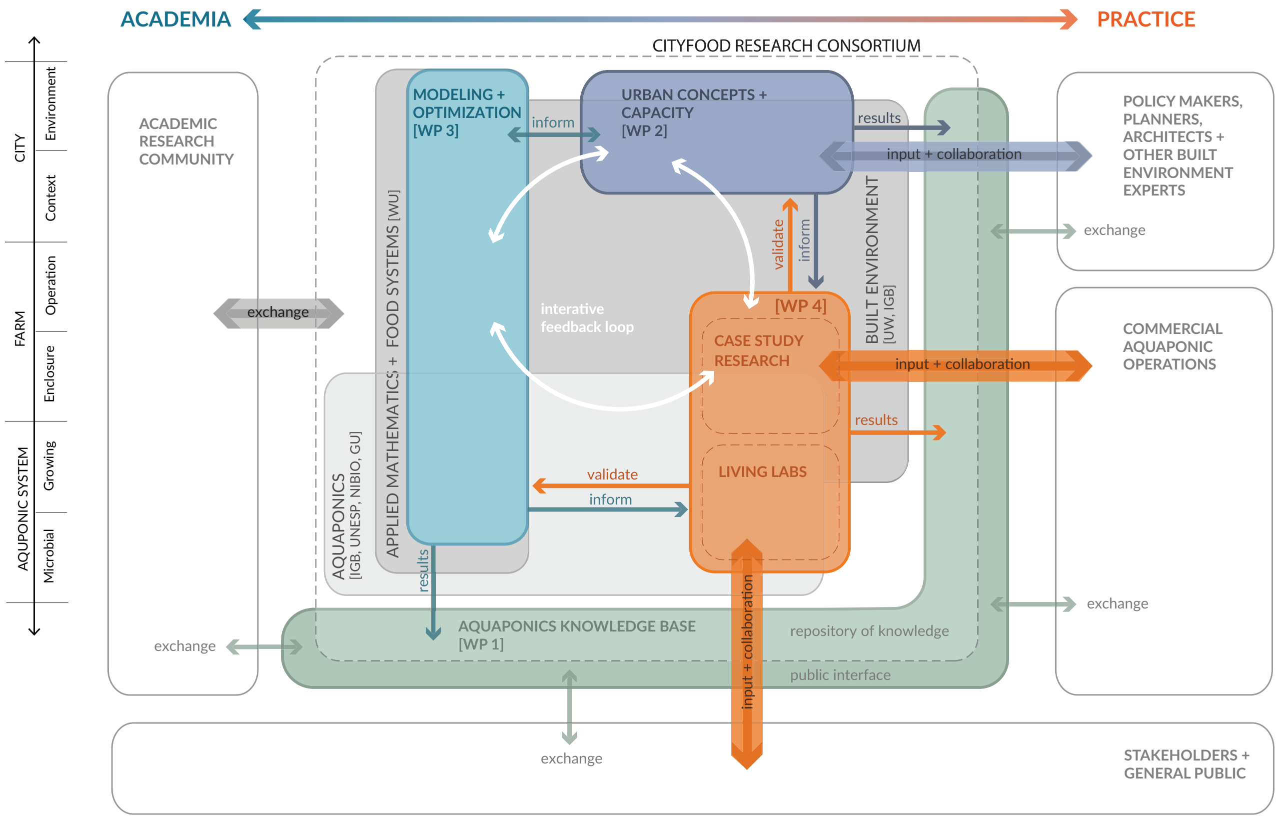
farm, providing enclosure and human expertise for the business operation; and (3) the city, contextualizing the farm and its environmental impact as shown in Figure 5 (Proksch et al. 2019). All three scales and their interaction must be considered to fully understand the potential urban integration of aquaponics. Additionally, any intervention—physical or regulatory—that aims to advance the urban integration of aquaponics must fulfill five fundamental implementation criteria that relate to best practices in the built environment. Farm operations and incentive structures that help to advance them must be (1) technically possible, (2) environmentally sustainable, (3) economically feasible, (4) socially beneficial, and (5) legally permitted. Combining scales and implementation criteria into one matrix, CITYFOOD UW has mapped relevant issues that can be addressed under the project scope (Figure 6). The matrix of research topics has proven valuable as a fundamental tool during the research refinement and planning process.

Interconnected Research Methodologies

CITYFOOD's research design structure of four autonomous but interconnected WPs has been instrumental for the project's progress. The WPs are primarily connected through the transfer of information and findings between teams, which is essential for the synthesis of results. The workflow diagram (Figure 7) shows interactions between the four main WPs, the overlapping expertise of the consortium teams engaging in them, and the various stakeholder groups involved in the project. The AKB (WP1) frames the CITYFOOD project by collecting existing knowledge and results into a repository and creating the public face of this new resource for stakeholders and the general public. The assessment of the practice of aquaponics (WP4) collects quantitative and qualitative data directly from commercial aquaponic farms and labs. It builds close connections and cocreation with practitioners; furthermore, the data and findings collected for WP4 validate the assumptions of WP2 and WP3. The modeling and optimization team (WP3) uses numerical models to assess the agglomerated impact of the practices observed. Research around urban integration (WP2) applies GIS-based methods to examine the capacity of cities to implement aquaponic operations. The other three research activities (WPs 2–4) synergize their findings in an iterative feedback loop of real-world data assessment, modeling, and mapping to understand the innovation potential and the impact of aquaponics on the FWE nexus. The overall evaluation addresses environmental, economic, and social benefits for urban communities.

Aquaponics Knowledge Base (WP1)

The work on the AKB combines the initial assessment of existing knowledge about aquaponics with the creation of a framework for CITYFOOD's final deliverable: the interactive AKB website. The website will provide in-depth knowledge to different stakeholders for scientific and commercial applications and will remain active after the funding period of the research project. The AKB will work as a research portal, a resource repository, and a platform to connect researchers and practitioners and to promote the sustainable potential of aquaponics. CITYFOOD UW began the design of the AKB by conducting an extensive literature review, documented in



△ Figure 7. Expertise of the CityFood research consortium, main research activities, and interaction with stakeholders.

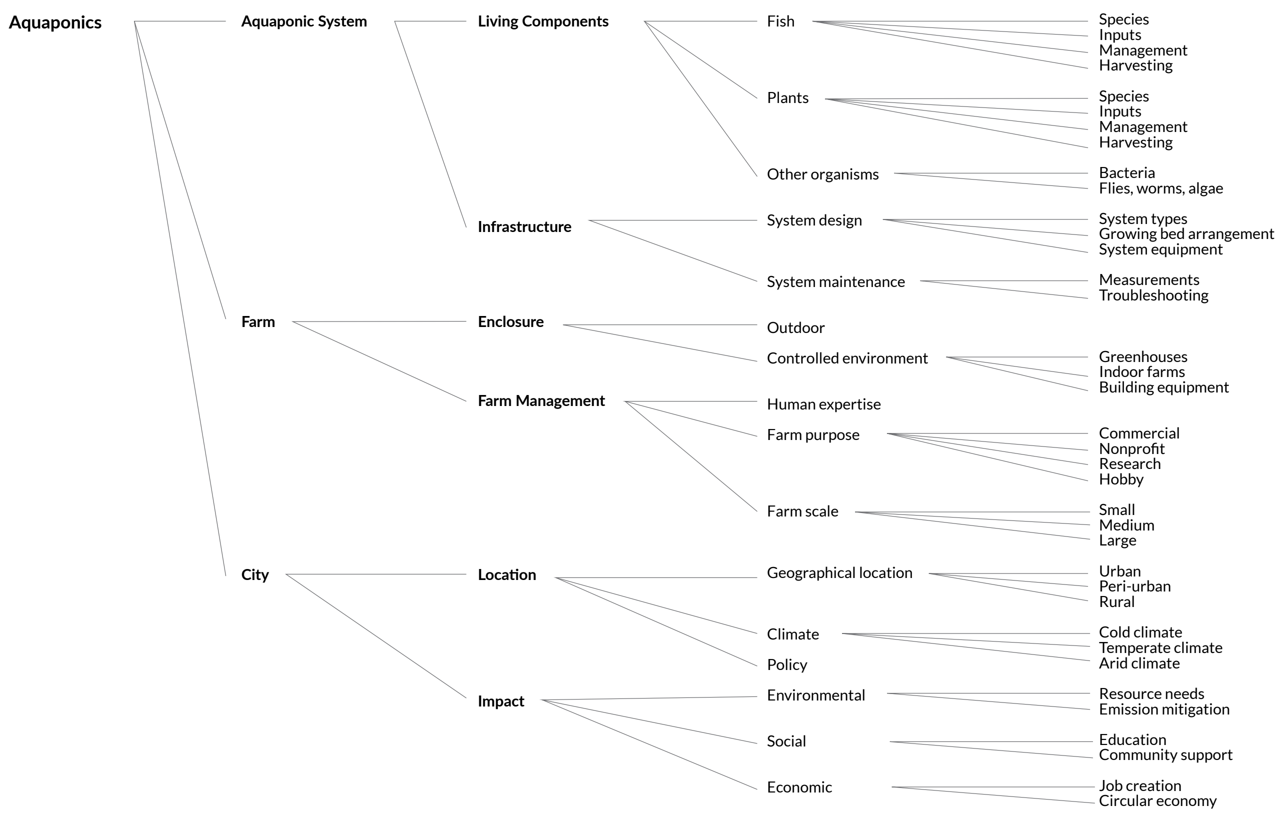
a citation management database (Zotero) (Roy Rosenzweig Center for History and New Media, 2019). In collaboration with a team from the University of Washington Information School, CITYFOOD UW and IGB developed a taxonomy of terms to categorize the knowledge (Figure 8). This classification tool will be used as the website's information architecture.

Urban Integration and FWE Nexus (WP2)

CITYFOOD's research on the urban integration of aquaponics takes the three sectors of the FWE nexus into consideration. Urban aquaponic farms can provide food sustainably by minimizing water, energy, and fertilizer use. In addition, they can provide environmental benefits, such as storm water management, a reduction in agricultural runoff, and mitigation of the urban heat island effect (Proksch et al. 2019). However, before aquaponic farms can be implemented in cities, the urban capacity to support aquaponic farming in a specific city must be evaluated. In the related field of urban agriculture, compiling land inventories has been an important research method over the last fifteen years, as the review of twenty published studies shows. In particular, work conducted in the context of New York City revealed how sites for urban agriculture can be identified (Ackerman 2012; Goodman and Minner 2019). The CITYFOOD UW team, under the lead of IGB, adapted this methodology by combining GIS-based mapping with built environment analysis to identify suitable sites for aquaponic farms. Unlike previous studies, this work focused explicitly on commercial-scale, controlled-environment agriculture (greenhouses and indoor farms), with particular attention paid to sites and building stock able to support new, technologically advanced farms.

Modeling and Optimization (WP3)

CITYFOOD WU in the Netherlands has developed numerical models that serve as a basis for a holistic assessment of the larger environmental impact, economic feasibility, and other trade-offs of aquaponic farming in cities. The team's recent work is part of the parametrization process to facilitate the planned life cycle assessment (LCA) and scenario analysis of urban and peri-urban aquaponics systems. The system optimization model builds on a previous, detailed, Python-based model the researchers for CITYFOOD WU used to recommend an improved resource management strategy for aquaponic systems (Lastiri et al. 2018). The most recent study merges two independent large MATLAB (The MathWorks Inc. 2019) model systems to provide a holistic aquaponics model for greenhouse environments (Goddek and Körner 2019). Building on the existing models, the team continues to investigate strategies to optimize aquaponic systems to a point where their products become competitive in the produce and fish market. The scenario analysis aims to develop simplified Excel-based



△ Figure 8. Taxonomy of aquaponics terminology used as information architecture for the AKB website.

models for impact modeling of integrated resource and energy flows with socioeconomic aspects of urban life. This modeling approach evaluates urban aquaponics in terms of resource-use efficiency, space, labor, and capital. Combined with the mapping method of WP2, the scenario analysis will demonstrate the potential benefits of urban aquaponics to the urban food system and FWE nexus.

Case Study Research, Living Labs, and Evaluation (WP4)

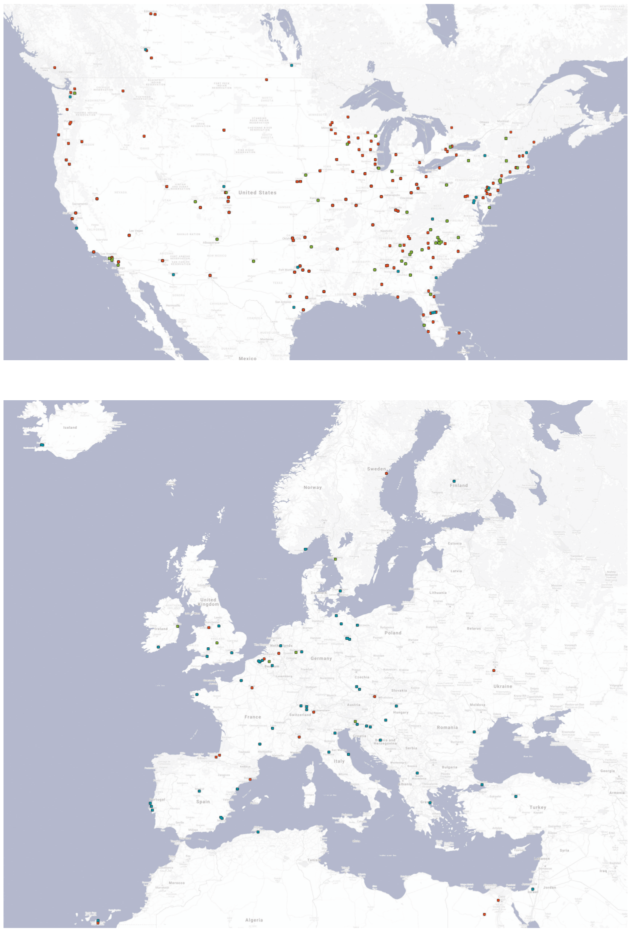
As a critical early step in the workflow of the project, CITYFOOD UW began collecting real-world data from operating commercial farms through data mining, interviews, site visits, and a survey. The collected data supports case study research, validates other CITYFOOD research activities, and facilitates collaboration with aquaponic practitioners. CITYFOOD UNESP, NIBIO, and IGB (in Brazil, Norway, and Germany, respectively) have started to construct and operate three aquaponic living labs, which are aquaponic operations run by the research teams in close collaboration with nonacademic stakeholders for academic and educational purposes.

Case Study Research

Over the last decades, researchers have increasingly recognized the value of case study research. Primarily associated with social science research, many other disciplines have adapted this methodology and have generated rigorous frameworks for its application (Scholz 2002). CITYFOOD UW is using this empirical inquiry method to comprehensively investigate the contemporary phenomenon of commercial aquaponic operations (Yin 2018). Each farm is considered a "case" and reviewed within its real-world context to reflect the complex situated relationships each farm has with its surroundings and communities (Proverbs and Gameson 2008; Stake 2006). CITYFOOD UW collects the cases in its case directory, with more detailed information about the cases deposited in project-specific databases.

The case directory is a comprehensive list of commercial aquaponic farms and research labs worldwide. It is based on systematic online searches to collect available data, including name, location, type, size, and contact information. The directory of approximately 470 aquaponic operations to date will be displayed on the AKB website to help connect researchers, practitioners, and stakeholders (Figure 9). With the growing pool of entries, the case directory also becomes an important tool to carefully select subsets of farms to answer specific research questions in separate studies.

Project-specific evidentiary databases support specific studies. The databases help organize the raw data and keep it separate from the narrative of the team's data interpretations (Yin 2018). Depending on the research question, CITYFOOD identifies a different subset of cases and collects relevant data points. A significant strength of case study data collection is the opportunity to use many different sources of evidence (Yin



△ Figure 9. Case directory of aquaponic operations: (red) commercial farms, (blue) research labs, and (green) nonprofit farms in North America (top) and Europe (bottom).

2018). In a sparsely documented emerging field like aquaponics, CITYFOOD UW assesses nontraditional documents and online sources (e.g., farm websites, social media accounts, and YouTube videos). These are valuable repositories of information, provided that the information is collected systematically. The CITYFOOD UW team uses its domain expertise in the built environment to verify multiple sources, such as written and photographic material, through careful triangulation to create higher accuracy (Groat and Wang 2013). For example, the team analyzes photographs of aquaponic operations by estimating dimensions and approximating assemblies; findings are then translated into scale drawings. This systematic, rigorous collection of information through observation also enables the team to establish a baseline state of the aquaponic field. Interviews with practitioners and site visits to aquaponic operations help to collect additional in-depth quantitative and qualitative information, fostering close collaboration with practitioners as well (Proverbs and Gameson 2008).

CITYFOOD UW integrates case study research components in each of its research studies, which is especially useful in the explorative phase of the CITYFOOD project (Gerring 2004). The team usually follows a multiple-case study design, which offers more robust evidence through the replication logic (Yin 2018). This approach is especially valuable when case comparability is given priority over case representativeness (Gerring 2004). An initial typological analysis of a small, selected set of cases of aquaponic operations, for example, led to a classification of enclosure types, such as high-tech greenhouses, indoor farming, passive solar greenhouses, and rooftop greenhouses, which illustrate the range of design options for urban integration (Proksch et al. 2019). The data collected serves as a basis for identifying success criteria for aquaponic farms and critical indicators for potential urban sites. These findings validate assumptions used in the modeling and optimization research of WP2 and WP3.

Global Aquaponic Practitioner Survey

To expand the in-depth knowledge about the practice of aquaponics, the CITYFOOD UW team adapted the survey method commonly used in the social sciences and health care (Yin 2018). The Global Aquaponic Practitioner Survey (GAPS) was launched using the online platform REDCap (Harris 2009) in 2019 to expand the data collection worldwide via aquaponic farmers' self-declared information and experiences. The GAPS was sent to all farms in the case directory with a request for snowball sampling, in which the recipients recruit other participants. The survey includes around sixty questions, which request information about system and farm configuration to document general trends in the growing field (Fowler 2009). Additionally, the survey poses questions that directly inform ongoing CITYFOOD investigations, such as priorities for initial site selection and relative difficulty in obtaining various regulatory clearances. In terms of data management, the CITYFOOD UW team is working on linking the survey database directly to a data visualization software (Tableau) (Salesforce 2019) to facilitate data analysis and dissemination.

Living Labs

Three CITYFOOD living labs have been opened and are in operation to date, including a university-based research lab for CITYFOOD UNESP in Brazil, a research and job-training lab for CITYFOOD NIBIO in Norway, and a demonstration lab in an education center for CITYFOOD IGB in Germany (Figure 10). A fourth living lab is under development as a teaching lab in a prison in Arendal, Norway. The living labs gather a wide range of data supporting a mixed-methods approach. Quantitative data, such as experimental data on water, energy, and nutrient consumption, and other system performance data, are collected to assess different biological filtration methods, appropriate stocking densities, and the suitability of different fish species for the lab location. Qualitative data are amassed to evaluate teaching outcomes, the potential for job creation, the social impact, and the stakeholders' experiences. The data collected will be used to validate the LCA, cost-benefit, and SWOT analysis, which connects the living lab analyses with the modeling research activities performed by CITYFOOD WU in WP3.

△ Figure 10. Living labs. (top) Berlin, Germany; (middle) São Paulo, Brazil; (bottom) Grimstad, Norway.

Next Steps

After completing the first year of the project, thoroughly testing the research design and publishing first results, the CITYFOOD consortium works on implementing and refining comprehensive dissemination strategies that will reach a wide range of aquaponics stakeholders, including researchers, practitioners and the general public. CITYFOOD GU leads the efforts to promote the idea of aquaponics, contribute to environmental education, and stimulate economic and social benefits. The Swedish team has most prominently created the project website, which documents the development and outreach of the project. The team produced a feature-length documentary that endorses aquaponic food production systems and will be broadcast on national TV in Sweden and potentially in the countries of the other consortium partners.

The CITYFOOD consortium aims also to address a final challenge: how to synthesize the findings generated by six teams that contribute research ranging in scale from microorganisms to urban infrastructures, six teams working on three different continents. The consortium is planning to document its final assessment of urban-integrated aquaponics in coauthored research papers, taking selected research questions comprehensively through all scales laid out in the research matrix. For example, one study might simultaneously address the benefits of phosphorus recovery as it applies to the microbial scale, effective production methods, case studies that use similar strategies, and the overall impact on the FWE nexus. The combination of these comprehensive synthesis papers, individual publications, documentation of outreach activities, how-to articles, and directories—all made available at the AKB website—will be CITYFOOD's model for publishing transdisciplinary research. With this approach, the CITYFOOD consortium aspires to create the most significant possible impact in science, practice, and advocacy for aquaponics. It also highlights the related interlinkages between food, water, and energy systems, which contribute to more sustainable urban futures.

Any research that investigates the future of cities or industries will benefit from transdisciplinary thinking. The assessment of broad changes and innovations, such as the implementation of emerging technologies that seek to respond to complex environmental challenges and transform entire industries, must bring together multiple perspectives and navigate a range of scales. Transdisciplinary teams might utilize a structural logic like that of CITYFOOD's research matrix to shape their research design across scales and criteria. Spanning the academic and practitioner communities, architects and built environment professionals are uniquely positioned and equipped to raise essential real-world questions across scales and to bolster impactful transdisciplinary collaborations.

Acknowledgments

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