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Enhancing urban resilience capacity through multifunctional urban food gardens: Food-Water-Soil nexus approach

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ENHANCING URBAN RESILIENCE CAPACITY THROUGH MULTIFUNCTIONAL URBAN FOOD GARDENS: FOOD-WATER-SOIL NEXUS APPROACH

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Department of Geotechnics, Environment, Natural Risks and Earth Sciences

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PREFACE

I, Pham Trung Kien, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

All the work described in this thesis was carried out in the Water and Environmental Laboratory, Department of Geotechnics, Environment, Natural Risks and Earth Sciences, under the supervision of Dr. Béatrice Bechet. This dissertation is my own work and contains nothing that is the outcome of work done in collaboration with others except as specified in the text.

This dissertation is not substantially the same as any that I have submitted, or is being concurrently submitted, for a degree, diploma, or other qualification at Gustave Eiffel University or any other University or similar institution except as declared in the Preface and specified in the text.

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"It takes a village to raise a PhD" (Ancient Wisdom, n.d). I was fortunate to be supported not just by one, but three. Firstly, by colleagues and fellow PhDs at the Water and Environmental Lab, who are always ready to rescue me from the French administrative system, offer free croissants and pain au chocolat, or share a quick laugh. Secondly, by colleagues at UGE Nantes Campus and, by extension, the wonderful people from the Clear-Doc program, who share coffee and join many trips together. And finally, by colleagues at the Architecture program at the Vietnamese–German University, who introduced me to the new field of architecture and social science.

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spontaneous party on a Saturday night. Their presence always lights up the room. Settling in Nantes could have been much more difficult if it were not for Đặng Thọ and bé Bò; I thank them for the many sweet memories and moments spent cooking food in my tiny flat. And I should thank Paul for how annoying he has always been, but also for being a genuine human being.

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ABSTRACT

Urban Food Gardens (UFGs) are increasingly recognized as vital Nature-Based Solutions for enhancing urban resilience and sustainability. However, their long-term viability is challenged by a lack of assessment tools that can holistically capture their complex socio-ecological dynamics. Dominant paradigms often prove inadequate for these low-energy, soil-based systems, as they tend to marginalize the foundational role of soil, treating it as a static substrate rather than a dynamic capital asset.

This dissertation addresses this critical gap by formulating, developing, and validating a novel Food-Water-Soil (FWS) nexus framework, a paradigm shift that positions soil as the central mediating component in urban agroecosystems. The research employs a multi-stage, mixed-methods approach, beginning with a systematic review that critiques existing assessment methods and establishes the theoretical necessity of a soil-centric paradigm. Using the dual lenses of Ecosystem Services (ES) and Ecosystem Disservices (EDS) as an analytical tool, the study adapts the participatory MESMIS methodology to construct an operational FWS Sustainability Index.

This framework is empirically tested through an in-depth case study of 54 allotment gardens in Nantes Nord, France. The application of the index generates a quantitative, multi-dimensional sustainability profile of the gardens, revealing

critical strengths, weaknesses, and trade-offs between the food, water, and soil dimensions. Ultimately, this thesis contributes both a new theoretical framework and a validated, practical tool for the integrated assessment of UFGs. The FWS Sustainability Index offers a robust framework for adaptive management by gardeners and evidence-based governance by urban planners, thereby supporting the long-term resilience and strategic integration of urban green infrastructure.

IMPACT STATEMENT

Within the academic community, this research offers two primary contributions. First, it advances sustainability science by proposing a new conceptual model—the FWS nexus. By demonstrating the theoretical and practical necessity of a soil-centric paradigm, it challenges researchers to move beyond infrastructure-biased models and more accurately reflect the ecological realities of systems like UFGs. Second, it provides a robust, mixed-methods methodological blueprint that integrates quantitative performance metrics with qualitative social perceptions. This approach provides a replicable model for future socio-ecological research, demonstrating how to bridge the gap between biophysical data and the lived experiences of community stakeholders.

Beyond academia, the FWS Sustainability Index is designed as a transformative tool for urban governance. For city planners and policymakers, it provides a means for evidence-based decision-making, allowing them to move from anecdotal accounts to a quantitative understanding of their green infrastructure's performance. The index can identify specific weaknesses across a network of gardens, such as systemic soil degradation or inefficient water use, enabling municipalities to deploy targeted support, including compost delivery programs or water conservation workshops, where they are most needed. By making the interdependencies of food, water, and soil management explicit, the

framework encourages the breakdown of administrative silos and fosters integrated policy development across departments of parks, water, and waste management, or gardeners and the non-profit organizations that support them. This work offers a tool for empowerment and self-assessment. The FWS index can be adapted for use at the community level, allowing gardeners to collaboratively identify their strengths and weaknesses, set priorities, and track their progress over time. This fosters a cycle of adaptive management and collective learning, aligning with the participatory ethos of the MESMIS methodology from which the index was derived. Furthermore, the tangible, data-driven results generated by the index can serve as robust evidence in advocacy efforts, strengthening the case for continued public support, land tenure security, and new funding opportunities.

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ABBREVIATIONS

AC: Garden Angle Chaillou

AM: Garden Amande

BR: Garden Bruyères

CR: Garden Cressonière

EG: Garden Eglantiers

ES: Ecosystem Services

EDS: Ecosystem Disservices

EFA: Exploratory factor analysis

FWS: Food-Water-Soil

GIS: Geographic Information System

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

KMO: Kaiser-Meyer-Olkin

MAAD: Maison des Agricultures et de l'Alimentation Durables

MESMIS: Indicator-based Framework for Evaluation of Natural Resource Management Systems

MCDA: Multi-Criteria Decision Analysis

NbS: Nature-based Solutions

SDM: System Dynamics Modelling

UA: Urban Agriculture

UFG: Urban Food Gardens

WEF: Water-Energy-Food

1 INTRODUCTION

1.1 URBAN GARDENS AS CATALYSTS FOR URBAN RENEWAL

Urban gardens, in their various forms, generate a board spectrum of benefits that extend far beyond the simple provision of food. Often viewed as multifunctional green infrastructure by urban planners and political actors, urban gardens deliver ecosystem services, strengthen social connections, and contribute to local economies (Delshad, 2022). Our understanding of these benefits enables various pathways to measure the outcomes of urban garden initiatives, moving beyond kilograms of produce to units of social cohesion, public health improvement, and ecological education. We should acknowledge that these “products” are no less vital to urban life than economic profitability or food production volume. This understanding is critical for justifying public investment, which should be perceived not as an agricultural subsidy but as a strategic expenditure on public health, community development, and green infrastructure that can be supported by multiple municipal budgets (Huq and Deacon, 2025).

Perhaps the most important argument for integrating urban gardens into broader solutions for city challenges is based on the vital ecosystem services they provide. Gardens play a direct role in climate actions, as plants' evapotranspiration process helps mitigate the urban heat island effect (Tomatis et al., 2023), absorb CO2 through carbon sequestration in plants and soil, manage stormwater runoff (Gittleman et al., 2017) reduce erosion, and boost biodiversity (Cabral et al., 2017).

In addition to the benefits of natural interactions among plants, water, and soil,

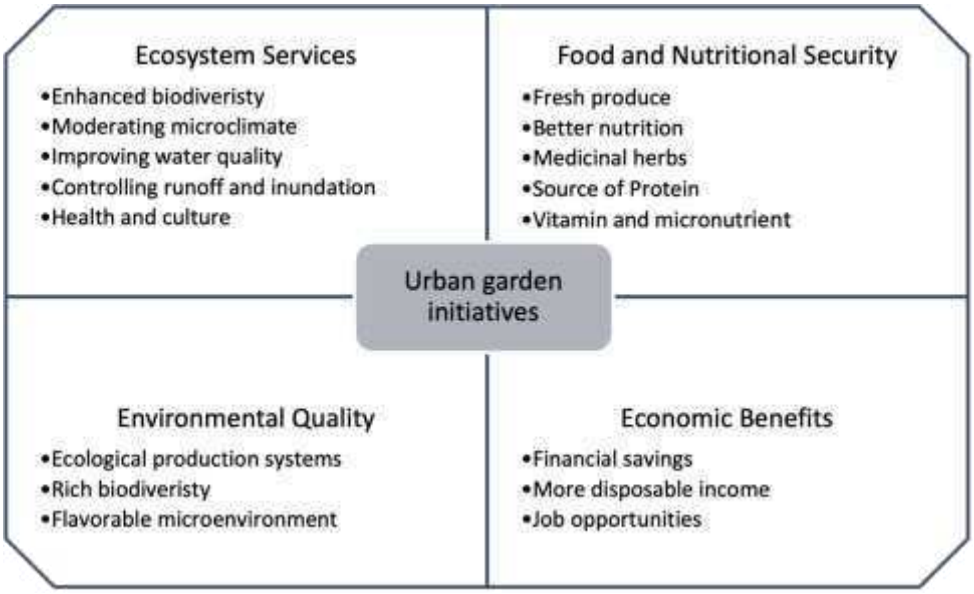

Figure 1.1. Example benefits of urban food gardens (adapted from Rattan, 2020)

garden spaces serve as a powerful tool for building stronger, healthier, and more connected communities. These functions, often referred to as cultural ecosystem services, are well supported by academic research, reports, and books. Gardens are consistently shown to be effective for fostering social cohesion, as they offer a neutral space where people from diverse backgrounds can gather, build trust, and develop social networks (Kirby et al., 2021). There's no doubt that

participation in gardening is closely linked to both physical and mental health benefits (Garcia et al., 2018) as it increases time spent outdoors and offers cognitive stimulation (Suto et al., 2021), thereby reducing stress and fostering a sense of belonging. Long-term gardening also improves access to fresh produce, leading to healthier eating habits with higher consumption of seasonal fruits and vegetables. Gardeners often value the learning opportunities about ecology, nutrition, and sustainability that come from working with plants and soil while aiming to protect biodiversity (Reyers et al., 2012).

During the global pandemic, COVID-19, home and community gardens became a crucial tool for reducing food insecurity in cities (Rattan, 2020a; Schanbacher and Cavendish, 2023; Schoen et al., 2021), especially for vulnerable households. In post-industrial cities like Detroit, urban farming on vacant lots has become a crucial component of community efforts to revitalize the local food system and address systemic food insecurity (Siegner et al., 2018). Citizens in the Global South, such as those in Hanoi, have been developing urban rooftop gardens as an essential way to ensure access to safe and healthy food (Turner et al., 2024). Although often not seen as their primary purpose, these examples show that urban gardens can offer tangible economic benefits and help create more resilient local food systems

While the literature frequently positions urban food gardens as catalysts for urban renewal (Rattan, 2020b), an uncritical acceptance of these benefits

introduces normative bias. The purported ecosystem services of UFGs must be rigorously evaluated against their inherent biophysical and socioeconomic limitations. Urban agriculture does not operate as a universal panacea; it is a complex intervention generating distinct trade offs.

Socially, the implementation of urban greening infrastructure frequently triggers eco gentrification, elevating localized property values and displacing vulnerable demographics, thereby converting communal social cohesion into spatial exclusion (Anguelovski, 2015). Economically, the food output of these spaces remains marginal relative to municipal demand, often relying on the hidden subsidy of uncompensated labor and intensive external inputs (McClintock, 2014).

Furthermore, the climate mitigation potential of UFGs is frequently negated by their operational life cycle. The carbon emissions generated by pumping municipal irrigation water, importing amended substrates, and manufacturing structural materials could exceed the localized carbon sequestered within the plant biomass (Goldstein et al., 2016). Biologically, the intense cultivation required for high yield family gardens could be resulted from continuous mechanical tillage, which can disrupt soil macro structure and accelerate organic carbon oxidation, contradicting claims of soil conservation. Acknowledging these structural nuances is an prerequisite to evaluate their systemic resilience.

Beyond these internal metabolic trade-offs, the physical persistence of urban food gardens is often compromised by external structural forces. Urban agriculture, particularly the traditional family allotment, operates under a state of land tenure insecurity. Despite their recognized provision of localized ecosystem services, these spaces are frequently classified by municipal governance as land banks rather than permanent green infrastructure. As urbanization pressures intensify, collective gardens are systematically subjected to eradication or relocation to accommodate more economically benefitial real estate development. An extensive spatial analysis of urban food cultivation in the United Kingdom, for example, revealed a historical loss of allotment land, demonstrating that prime urban pedological resources are routinely sacrificed to urban expansion and permanent soil sealing (Dobson et al., 2020). This structural vulnerability reveals an urgent reality: assessing the biophysical performance of these gardens is not merely an exercise in ecological optimization, but a necessary prerequisite to politically and spatially defend their existence against the constant threat of urban erasure.

1.2 KEY CONCEPTS IN URBAN GARDENS RESEARCH

1.2.1 Urban resilience and sustainability in the 21st century

By 2050, the Earth is expected to be home to approximately 9 billion people, with around 68% projected to reside in urban areas (United Nations, 2019). Cities worldwide face tremendous pressure to provide the necessary resources for their citizens while addressing social and environmental issues that arise from their impressive economic outcomes (Atta-ur-Rahman et al., 2016).

Although occupying a small fraction of Earth's surface, at around 3% (Liu et al., 2014), urban areas around the world are responsible for 60 to 80% of the energy used and 75% of the total carbon emissions (United Nations Environment Programme, 2020), significantly contributing to global warming. However, cities are vulnerable to abrupt changes in hydrometeorological phenomena induced by global warming, including flood hazards, storm surges, drought, and cyclonic storms (McCarthy et al., 2010; Puppim de Oliveira et al., 2022). These disasters threaten cities' food and water security. As cities grow and expand around the globe alongside technological advancements, more natural resources are required and consumed to meet our development needs. Consequently, the urbanisation process is often associated with excessive consumption and contamination of water, massive generation of greenhouse gases and air pollution, alteration of

local and regional climate through urban heat island effects, and the decline of biodiversity and ecosystems, to name a few (Grimm et al., 2008).

As a result of facing continuing challenges, cities and urban areas have been actively seeking more sustainable development pathways. Due to their capacity to serve as innovation and knowledge creation hubs, cities have been increasingly recognised for their role as the frontline in tackling climate change challenges and building a more resilient society (Puppim de Oliveira et al., 2022). Cities not only represent places of enhanced and clustered vulnerability to climate change and societal problems, but also places where climate actions and social changes can be leveraged through co-creation and co-benefits (*World Cities Report 2024*, 2024). In response to these complex and unpredictable threats, *urban resilience* and *sustainability* have become central goals for cities worldwide (Kong et al., 2022). This view illustrates the shift away from merely protecting against known hazards to building long-term capacity to withstand disruption and change.

The concepts of *resilience* and *sustainability*, while often driven by a strong concern about reducing disruptions and preventing unstable future development, differ considerably. In the urban context, *resilience* refers to a city or urban system's ability to adapt, withstand, recover, and transform quickly in response to environmental and social disruptions (Klein et al., 2003; Meerow et al., 2016), such as natural disasters, climate change, and other unexpected events. By integrating various aspects of adaptability, learning, and transformation, *resilience* is

positioned within the social-ecological system as a "bouncing forward" concept, which recognizes the process of disturbances and reorganization rather than the traditional "bouncing back" view (Comfort et al., 2010). The notion of *resilience* lies in the acceptance of disruption and radical surprises (Evans, 2011), as they are inevitable, and demands anticipation and preparation for changes to occur. *Urban resilience* nowadays is defined by several key characteristics, which are robustness, redundancy, flexibility, resourcefulness, reflectiveness, inclusiveness, and integration (Lowe et al., 2024; Meerow et al., 2016). In this view, *resilience* is portrayed as a precondition for *urban sustainability* (Romero-Lankao et al., 2016)

Meanwhile, the concept of *sustainability* extends beyond traditional ideas of environmental protection and conservation; it involves a long-term focus on conserving natural resources, meeting social needs, and maintaining economic resources. Originating as a normative political concept, the definition and understanding of sustainability have been rapidly adopted by various scientific disciplines, often without explicit acknowledgement of its political origins. Following the 1992 United Nations Conference on Environment and Development in Rio de Janeiro, sustainability was subsequently implemented at the national and local levels inountries committed to sustainable development (United Nations, 1992). *Sustainability* is often expressed through the three pillars or Venn diagrams of economy, environment, and social equity, all of which are equally important and interconnected. At the core of sustainability lies the

principle of equitable access and distribution of natural resources to citizens, along with growth that minimizes environmental impact (Keivani, 2009; LaGro, 2019). Cities' resource and service needs extend beyond their borders, primarily focusing on essentials such as food, water, medical care, housing, sanitation, and ecosystem services to support the well-being of their citizens. In this context, the *urban sustainability* concept underpins collective efforts in urban planning and legislation to improve self-sufficient systems in cities, prevent excessive external resource consumption, and protect citizens from climate hazards.

1.2.2 Urban nexus assessment

The *urban nexus* is a conceptual framework focusing on policy and planning approaches designed to understand and manage the intricate interdependencies between critical resource systems within an urban context. The idea is less focused on quantifying the input, transformation, and outflows of materials, which are linked to *urban metabolism*, and is more concerned with how resource flows are managed and distributed under the influence of social, political, and economic factors (Chen and Lu, 2015). *Urban metabolism* is a biological analogy, metaphorically describing the city as an organism that consumes resources and generates waste to sustain itself. Methodologies such as material flow analysis and life cycle assessment enable stakeholders to quantify the inputs, outputs, and internal transformations of particular materials and energy (Wang et al., 2023).

Urban nexus, on the other hand, is more concerned with the dynamic relationships among social, political, and economic factors and how they influence the movement of materials and energy. It shifts the analytical focus from resources alone to the interdependencies, trade-offs, and synergies across multiple sectors simultaneously (Chen and Chen, 2015). In other words, while *urban metabolism* offers an accounting framework for what flows through a city, the *urban nexus* provides a systems framework to understand why and how those flows are governed. Table 1.1 outlines the main differences between these two concepts.

Table 1.1 Key distinctions between urban metabolism and urban nexus

Feature	Urban metabolism	Urban nexus	Reference
Core metaphor	City as an organism	City as a web of relationships	*Chen and Chen, 2015; Chen and Lu, 2015; Gondhalekar and Erlbeck, 2021; IWRM Action Hub," 2023; Wang et al., 2023*
Unit of analysis	Flows of a single resource (e.g. water, energy)	Interdependencies and trade-offs between multiple sectors	
Treatment of social factors	Often implicit or external drivers	Central to analysis ("latent nexus" of social relations)	
Common methodologies	Material flow analysis, life cycle analysis, input-output analysis, ecological network analysis	Life cycle assessment, system dynamics, indicator systems, system, network analysis	
Primary Goal	Quantifying resource efficiency and environmental impact	Optimizing synergies and improving cross-sectoral governance	

The Water-Energy-Food (WEF) nexus sits at the heart of the urban nexus. It was formally recognized at the 2011 Nexus Conference in Bonn (Martin-Nagle et al., 2012), emphasizing that these three critical sectors are deeply interconnected.

Actions or decisions in one sector often trigger cascading effects and create trade-offs or synergies in the others. For example, water is vital for almost all energy production, energy is needed for water treatment and transportation, and both are key inputs for food production. The WEF framework promotes integrated

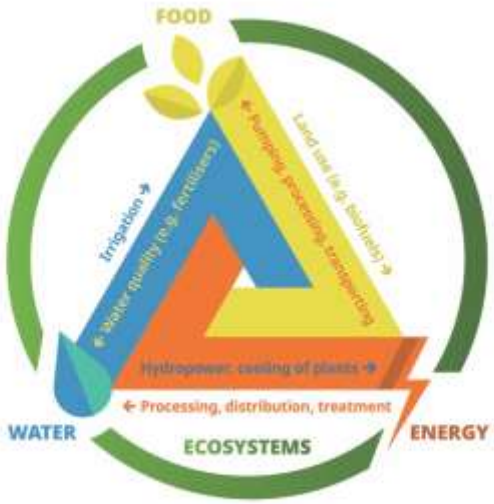

Figure 1.2 Water-Energy-Food-Ecosystem Nexus from (GWP-Med, 2019)

resource management, aiming to find cross-sector solutions, improve security and efficiency, and minimize ecological impacts (Arthur et al., 2019). It also underscores the importance of reconciling potentially conflicting interests among these sectors, while identifying opportunities and exploring emerging ones.

While originating with the WEF triad, the scope of the urban nexus has expanded to encompass other critical urban systems. This evolution reflects a maturing understanding that the relationships between WEF are mediated by, and have profound impacts on, other domains. Urban nexus dialogue often encompasses

land use, waste management, climate resilience, ecosystem health, and broader socio-economic factors, including public health and social equity (GWP-Med, 2019). This expansion is not an arbitrary addition of variables but a necessary progression of the paradigm from a resource management tool to a comprehensive framework for urban sustainability. Ecosystems, for example, are not just another sector but the fundamental platform upon which the nexus operates, while climate change is the primary external stressor altering the relationships within it (Mabhaudhi et al., 2024).

This recognition of ecosystems as a foundational platform is particularly crucial when evaluating decentralized green infrastructure. Currently, the Urban Nexus is predominantly operationalized through the macroscopic WEF framework to evaluate systemic resource security and municipal metabolic flows (Newell et al., 2019; Zhang et al., 2019b). owever, applying this macro-scale paradigm directly to UFG reveals a structural limitation. In low energy urban cultivation, the biophysical reality is that soil, rather than municipal energy, acts as the central regulating infrastructure governing both water retention and caloric output (Edmondson et al., 2014). Therefore, while the WEF framework establishes the foundation of nexus thinking, evaluating the true resilience of urban agriculture necessitates a theoretical alternative. This shift must center the soil node, creating a transition toward a FWS framework that will be formally conceptualized in subsequent chapters.

Consequently, implementing any nexus approach requires overcoming severe administrative barriers. The core of the Nexus concept is to promote an integrated approach across sectors to address institutional fragmentation, often referred to as "silo thinking." Urban governance typically operates along rigid sector-specific divisions, with separate departments handling water, energy, transport, and land use, often in isolation, which can be referred to as sectoral silos (Buylova et al., 2025). This setup is more than just an administrative inconvenience; it reflects a ingrained institutional culture, reinforced by sectoral budgets, specialized professional training, and unique legislative mandates, which can sometimes conflict (Artioli et al., 2017; Monstadt and Coutard, 2019). For example, a transport department might pave over a green space to expand a road, solving a traffic problem but inadvertently increasing stormwater runoff and heat island effects, thus creating new problems for the water and environment departments. Another type of silo that can be observed in the EU urban administrative boundary is the cross-institutional silos (Buylova et al., 2025), where coordination between government and non-government actors is needed. Overcoming this institutional inertia requires a deliberate strategy of multi-scalar integration, connecting actors both horizontally and vertically across levels of government (Bierwirth et al., 2024).

1.2.3 Urban Nature-based solution

Cities are at the forefront of global efforts to address the world's most pressing sustainability challenges, such as climate change and biodiversity loss. However, the solutions available are just as complex as the problems themselves, encompassing technological, social, and ecological approaches. Nonetheless, individual solutions alone do not seem to be a cure-all for the systemic issues, which is why the nexus approach we discussed earlier has gained importance. This has led to the rise of nature-based solutions (NbS)—an ecocentric approach offering multiple benefits for the environment, economy, and society in urban areas (Frantzeskaki, 2019; Lafortezza et al., 2018; Nesshöver et al., 2017). Despite its growing prominence, NbS is often considered as an "umbrella concept". It is not a new invention but rather a synthesis that covers a wide range of pre-existing, nature-focused approaches. These include ecosystem-based adaptation, ecosystem-based mitigation, eco-disaster risk reduction, green and blue infrastructure, and ecological engineering (Cohen-Shacham et al., 2016).

The International Union for Conservation of Nature (IUCN) has the most widely cited and influential definition of NbS that shapes the global discourse, in which NbS is defined as:

> *"Actions to protect, sustainably manage, and restore natural or modified ecosystems, which address societal challenges, effectively and adaptively, providing human well-being and biodiversity benefits"*

The IUCN definition of NbS emphasizes “actions' from a human-focused perspective, integrating societal factors into its core framework to ensure solutions for human issues do not harm nature. Eggermont et al. (2015) shaped the NbS term by proposing a typology of NbS, categorizing them into three types based on the number of stakeholder groups, delivery services, and the level of engineering involved (see Figure 1.3). These NbS types and their hybrid versions should be viewed as complementary, with no single type being superior to the others, but rather space- and time-appropriate.

In recent years, the European Commission (EU) has been a primary driver of NbS research and implementation, having its own definition of NbS that reflects a firm policy and innovation focus (EC, 2019). While aligned with the IUCN’s core idea,

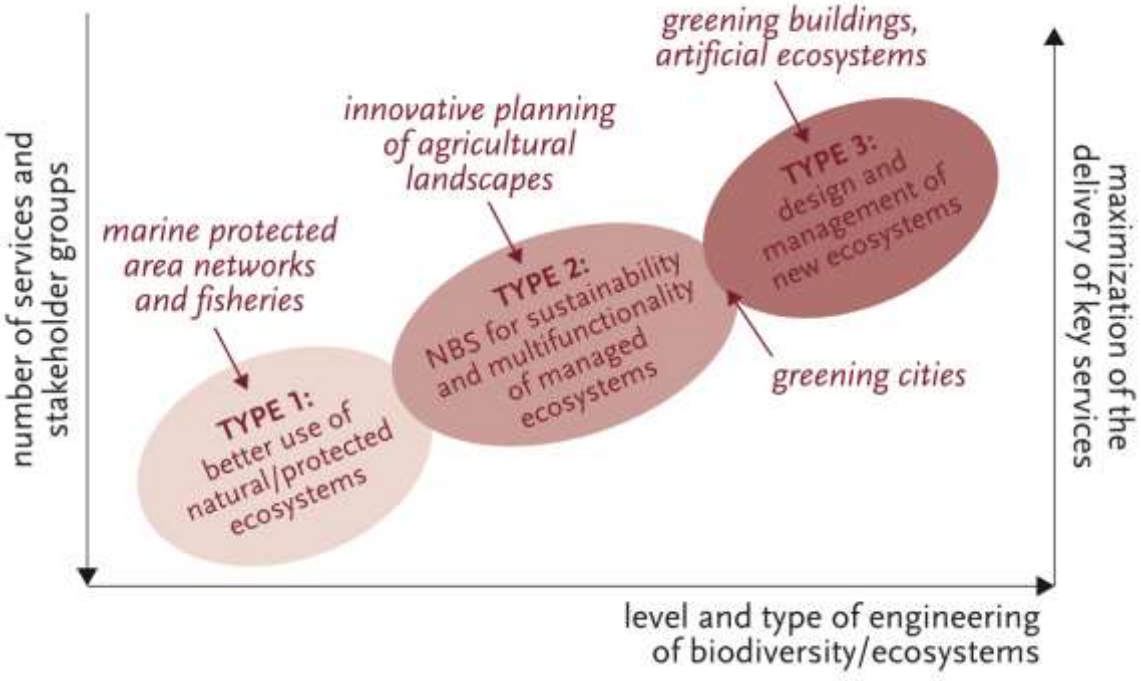

Figure 1.3 Typology of NbS from Eggermont et al., 2015

the EC's definition frames NbS in a broader term – "solutions inspired and supported by nature"-and prioritizes cost-effectiveness and economic benefits as core components, alongside environmental and social ones. The definition also explicitly mentions building resilience towards urban applications.

The application of NbS in cities is diverse, ranging from the protection of remaining natural areas to the creation of highly engineered green technologies integrated into the built environment. As shown in Figure 1.3, stakeholders can categorize these interventions by the degree of human intervention and ecosystem modification, ranging from minimal intervention to extensive management or the creation of new ecosystems. The following are some key challenges targeted by urban NbS:

- *Climate resilience and adaptation*: Interventions aim to mitigate the urban heat island effect by providing cooling effects through evapotranspiration and shading (Ramakreshnan and Aghamohammadi, 2024), manage stormwater to reduce flood risk from extreme precipitation events (Kõiv-Vainik et al., 2022), and enhance the city's capacity to adapt to a. more volatile climate (Hobbie and Grimm, 2020).

- *Environmental quality improvement*: Vegetation can improve air quality by filtering pollutants and particulate matter (Nowak et al., 2006), reduce noise pollution(Zhao et al., 2021), enhance the quality of water through the natural

filtration process(Muerdter et al., 2018), and sequester atmospheric carbon(Thölix et al., 2025); all of these functions contribute significantly to a healthier urban environment.

- *Health and well-being*: The presence of green and blue spaces in cities is strongly linked to improved human health. These areas provide spaces for physical activity and recreation (Garcia et al., 2018), offer opportunities for stress relief and mental restoration (Sturm and Cohen, 2014; Vujcic et al., 2017), and can foster social cohesion by creating communal gathering places (Wilson et al., 2024). The benefits are particularly important for vulnerable groups, e.g. children and older adults. The psychological efficacy of NbS is linked to landscape aesthetics. Beyond mere visual ornamentation, the aesthetic quality of urban gardens serves as a primary mediator for mental health benefits. These spaces facilitate attention restoration and stress reduction by providing a sensory refuge from the cognitive fatigue induced by the urban built environment (Kaplan, 1995). Furthermore, aesthetic value acts as a functional driver for place attachment and social stewardship, ensuring that the health benefits provided by these NbS are maintained through long-term community engagement.

- *Biodiversity conservation*: In an increasingly urbanized world, cities have to be part of the solution for conserving biodiversity. Urban NbS can create and connect habitats, supporting native flora and fauna within the urban matrix (Beaugeard et al., 2021; Threlfall et al., 2017).

- *Socio-economic benefits*: Beyond environmental and health benefits, urban NbS can deliver economic returns. For example, creating or restoring green spaces can increase tourism revenues (Mandić, 2019), raise property values (Costadone and Zhang, 2025), and create jobs in design, installation, and maintenance.

The multifunctionality of these interventions is a core advantage. A single NbS can address multiple challenges simultaneously, delivering a suite of co-benefits. Table 1.2 provides an overview of common urban NbS types and their associated benefits, illustrating this principle.

While urban NbS show considerable promise, they are not a cure-all and have inherent limitations and potential trade-offs that need careful consideration during planning and implementation. First and foremost, the primary concern of NbS is the uncertainty regarding their reliability and cost-effectiveness compared to traditional engineered solutions (Seddon et al., 2020), which necessitates the development of context-specific metrics to assess their effectiveness at various scales and associated trade-offs. Additionally, the concept has faced ongoing criticism for its vulnerability to "greenwashing'—where corporations and governments may misuse it to project an eco-friendly image without making meaningful changes to their core operations (Gałecka-Drozda et al., 2021; Melanidis and Hagerman, 2022). Finally, a growing body of research and activism has brought the social justice dimensions of NbS to the center of the discourse,

arguing that an NbS that is not socially just risks reinforcing or exacerbating social inequalities (Pineda-Pinto et al., 2021).

Table 1.2 Examples of NbS and associated benefits

NbS Typology	Primary Function	Multifunctional Ecosystem Services	Application Scale
Green roofs	Stormwater management	Building insulation (energy savings), urban heat island mitigation, habitat creation, and aesthetic improvement.	Building
Vertical Gardens & Green Walls	Air Quality Improvement	Building cooling, noise reduction, aesthetic enhancement, and biodiversity in dense areas	Building
Rain gardens & swales	Stormwater management	Groundwater recharge, water quality improvement (pollutant filtering), habitat creation, green amenity	Site, street, neighbourhood
Street trees & urban forests	Urban heat island mitigation	Air quality improvement, carbon sequestration, noise reduction, mental health benefits, and aesthetic value.	Street, neighbourhood, city
Urban parks & green spaces	Recreation & Social Cohesion	Mental & physical health, biodiversity support, stormwater infiltration, air cooling, and tourism revenue.	Neighbourhood, city
Community gardens	Food provision	Mental & physical health, biodiversity support, social cohesion, and recreational and educational opportunities.	Neighbourhood, city
Constructed wetlands	Water Purification / Wastewater Treatment	Flood attenuation, habitat for wildlife, carbon storage, and recreational and educational opportunities.	Neighbourhood, city

UFGs are increasingly operationalized within municipal policy as NbS, designed to deliver targeted ecosystem services that mitigate environmental degradation and enhance urban resilience (Wickenberg et al., 2021). However, treating all collective gardens as a monolithic NbS category would introduce analytical distortions. To facilite the development of a practical and theoretical possibilities

of the FWS framework, the primary object of this focuses on family gardens (traditional allotments) (Consalès, 2003).

While both typologies qualify broadly as NbS, their service delivery vectors are divergent. Community gardens, emerging from grassroots movements in the 1990s, function primarily as social infrastructure. They operate on undivided, collectively managed land and are optimized to generate cultural regulating services, specifically social cohesion, community education, and psychological well-being (Baudelet et al., 2008). Consequently, their biophysical extraction rates and agricultural yields remain comparatively low.

Conversely, family gardens, rooted in the 19th-century industrial drive for working-class subsistence, often function as metabolic infrastructure. Built around parceled, privately managed plots, their primary operational objective is the maximization of localized yield, or provisioning services (Pourias et al., 2015). This intense output necessitates substantial hydrological inputs and continuous manipulation of the pedological profile. Therefore, family gardens represent an intensive iteration of NbS. It is precisely this metabolic intensity that necessitates the application of the FWS nexus; family gardens generate biophysical pressures and potential ecosystem disservices that community gardens rarely reach.

1.3 PROBLEM STATEMENT

Cities worldwide are adopting NbS, such as UFGs, as a key strategy to tackle future sustainability challenges. This global greening effort, driven by initiatives like the One Health moment (Bruno et al., 2024), has created an urgent need for practical assessment tools to measure the performance and long-term viability of these complex social-ecological systems. However, many NbS still lack frameworks and parameters for evaluating their effectiveness from a social-ecological perspective, especially across different scales and dimensions (Kato-Huerta and Geneletti, 2022).

One of the primary challenges in establishing such a framework lies in the heterogeneity of urban contexts worldwide, which are deeply influenced by diverse cultural and institutional factors. Consequently, it is essential to develop context-specific indicators that are customised to local circumstances to enhance the usability, scalability, and transferability of NbS (Debele et al., 2023). This endeavour often requires a substantial allocation of both financial and human resources, which are generally not readily accessible to the majority of urban centres. Secondly, the majority of existing research focuses primarily on evaluating how modelling tools and parameters can be utilized to identify optimal locations for NbS and UFGs, or to facilitate their design (Caneva et al., 2020; Wickenberg et al., 2021), often overlooking the importance of long-term assessment of implemented NbS, including the potential disservices associated with them. An additional challenge pertains to the insufficient systematic

understanding and documentation of the synergies and trade-offs among various impacts of NbS (Dumitru et al., 2020).

Given the significant role of UFGs in enhancing urban resilience, UFGs, especially gardens operated collectively with a non-profit structure, are widely recognized as nature-based solutions (NbS) in many different contexts (Lafortezza and Sanesi, 2019; Moniz et al., 2022; Skar et al., 2020; van der Jagt et al., 2017). Despite increasing interest in UFGs, these initiatives often receive limited long-term support and struggle to maintain sustainability amid ongoing development (Lawson, 2004). Beyond the need for institutional backing, gardeners face financial and technical challenges after establishing the gardens, primarily due to persistent resource demands, including oil, compost, fertilizers, and water (Becker and von der Wall, 2018). The use of these resources as inputs for UFGs is linked to the safety of the harvested products and greatly influences their sustainability, yet they are frequently evaluated separately. Similarly, the economic dimension should be recognized functionally as a systemic nuisance, not standard economic performance, since allotment gardens are often created for non-profit purposes. Therefore, economic assessment should be included in NbS assessment as the material limits and operational vulnerability of the cultivators, establishing an economic baseline that persistently restricts the biophysical performance evaluated by the FWS.

Crucially, the interaction between these resources is frequently evaluated separately, masking critical systemic functions. For example, while urban green spaces are routinely assessed for their capacity to mitigate extreme flood events, the fundamental role of the pedosphere in regulating the municipal water cycle during non-extreme regimes is regularly overlooked. Healthy urban soils act as continuous metabolic infrastructure, facilitating daily infiltration, supporting base flows, and maintaining the evapotranspiration necessary for thermal regulation A fragmented approach to analyzing these components risks a disconnect between sectoral planning efforts and undermines the overall assessment's integrity. Therefore, it is essential to adopt an integrated and holistic approach to these components to foster synergies and ensure the effective use of these vital resources (Gu et al., 2021; Skar et al., 2020).

1.4 RESEARCH AIM

This dissertation aims to contribute to the field of NbS research by developing a theoretical and technical framework to support the long-term assessment of UFGs. The framework examines the complex relationships among the key components of UFGs, such as natural capital and human capital, and provides recommendations to optimize synergies and mitigate trade-offs between these components. Ultimately, this approach seeks to promote the sustainability of UFGs and their contribution to urban resilience. The main research question of this doctoral research is as follows: **How to assess the sustainability of UFGs through a food-water-soil nexus framework – a more relevant and accurate paradigm for soil-based urban ecosystems?**

The dissertation is structured around sub-questions that systematically address the primary research objectives. It comprises a series of studies, beginning with an examination of the existing theoretical and methodological nexus framework for UFGs (Chapter 2). This is followed by the development of a theoretical framework and management system designed to evaluate the sustainability of nexus systems (Chapter 3). A case study for validating the analytical framework is presented in Chapter 4, providing foundations for building an operational, sustainable assessment framework by FWS nexus, and a critical discussion of the key findings and limitations of the index system (Chapter 5). Chapter 6 provided an overview

and summary of the results, together with their limitations and future directions. The sub-questions guiding this research are as follows:

- Sub Research Question 1: What is the current state of knowledge concerning the nexus assessment frameworks of UFGs, and what research gaps remain?

- Sub Research Question 2: How can a Food-Water-Soil (FWS) nexus be conceptualized as a more appropriate paradigm for these systems?

- Sub Research Question 3: How to incorporate perceived priorities, benefits, and risks associated with UFGs from gardeners into the assessment criteria?

- Sub Research Question 4: How do the sustainability profiles of UFGs provide insights regarding their key strengths, weaknesses, and trade-offs among food, water, and soil functions?

- Sub Research Question 5: How does the application of the framework provide a more robust and responsible model for the strategic management of urban green spaces?

1.5 METHODOLOGICAL FRAMEWORK

1.5.1 Research setting – the CLEAR-Doc project

This doctoral research is a part of CLEAR-Doc – a European Horizon 2020 Marie Skłodowska-Curie COFUND programme that focuses on all research areas related to "Cities". The project employed a total of 30 doctoral students working on designing and developing resource-efficient urban spaces, understanding and managing "urban risk" for safe and resilient cities, and developing the digital city as a catalyst for social, environmental, and economic performance ("City Lab Education And Research Doctoral Programme," 2022). Within six thematic fields of the programme, this dissertation identifies and covers two of them, which are:

- C2 Safety, security, and risk management within the city

- C5 Sustainable urban life and tourism

In this doctoral research work, the investigation was conducted Nantes city (France). This research benefits from datasets collected through various previous projects conducted on urban garden systems by the IRSTV (l'Institut de Recherches en Sciences et Techniques de la Ville) and Eau et Environnement Laboratory at Gustave Eiffel University. The case studies for this doctoral research include soil data from Nantes, gathered through two research projects, URBiNAT and WISE Cities, between 2019 and 2021 (Doux et al., 2022; Moniz et al., 2022). An additional dataset on earthworm populations was obtained from the JASSURE project (Le Guern et al., 2018). All studied gardens in Nantes are situated in

deprived neighbourhoods with a significant need for improvement. More detailed socio-demographic profiles of the studied populations are provided in chapters 4 and 5. During the research process, I spent 8 months at the Vietnamese–German University, from October 2023 to June 2024, collecting soil and social data from Thu Dau Mot city urban gardens. However, due to the early stage of research, data collected from this city were incomplete with a modest number of samples; thus, the data from Thu Dau Mot city are not included in this study.

The core analytical focus remains firmly anchored in the socio-environmental dimensions governed by the FWS nexus. This prioritization is featured by the specific operational nature of collective allotment gardens, which function predominantly on the margins of the formal market economy. Their primary outputs (e.g., localized caloric provisioning, ecological stewardship, and social cohesion) generate direct household and community use-value rather than commercial exchange-value. This focus, however, does not imply that urban agriculture operates in a financial vacuum. Cultivators face persistent financial pressures regarding the procurement of localized inputs, including municipal water tariffs, imported compost, seeds, and structural materials. Therefore, rather than evaluating economic performance as a pillar of success, this thesis integrates the economic dimension functionally: as a structural constraint. The financial cost of material inputs is recognized as a systemic "nuisance" or stressor variable that dictates the material limits and operational vulnerability of the cultivators.

Acknowledging this economic friction in the introductory framework establishes the necessary foundation for the specific financial constraints that will be parameterized within the operational assessment model detailed in later chapters

1.5.2 Step 1: Forming a Theoretical Framework

A scoping literature review aims to provide an overview of the current applied nexus frameworks for UFGs. It examines the methods, variables, and indicators used to evaluate urban gardening initiatives and summarizes these approaches in Chapter 2. Besides highlighting the connections between nexus components, the chapter also reviews existing literature to identify gaps and limitations in these methods. It establishes the theoretical necessity of a soil-centric paradigm by demonstrating the limitations of the dominant WEF model and alternative strategies for integrating the soil dimension into research agendas for UFGs.

1.5.3 Step 2: Building a Food-Water-Soil Assessment Framework

This step involves the theoretical formulation detailed in Chapter 3. Building on the gap identified in Step 1, this phase develops the conceptual architecture of the FWS nexus. It formally "positions soil as the central mediating component" and a "dynamic capital asset". It also establishes the dual lenses of ecosystem services and ecosystem disservices as the core analytical tool for assessing the system's socio-ecological performance.

1.5.4 Step 3: Data collection

This doctoral research employs three complementary data sources for data collection. Two of these sources were introduced in Section 1.5.1. The third dataset encompasses a comprehensive sample of urban gardeners in Nantes, capturing their perceived priorities, benefits, risks, and gardening practices. Data were collected via a detailed questionnaire administered to Nantes' North gardeners, municipal officials, and non-profit workers, yielding a total of 54 responses from gardeners collected between April and June 2025. The dataset provides personal context indicators, such as years of gardening, age, gender, and employment status, in addition to the self-perceived risks and benefits of UFGs. The complete questionnaire can be found in Appendix 4.

1.5.5 Step 4: Coding, weighting indicators, and statistical analysis

This final step represents the methodological operationalization of the thesis, presented in Chapter 5. It adapts the participatory MESMIS methodology to construct the operational FWS Sustainability Index. The social data from Step 3 and biophysical data are coded and weighted to populate the index. The data were categorized according to their respective indicators, and sustainability scores were assigned within each dimension (food, water, and soil) based on the weighted contribution of each indicator. Statistical analyses were conducted to assess the normality of the scores and to compare attributes across different groups.

Detailed information about the indicators and their weights can be found in Chapter 5.

1.6 RELEVANCE AND IMPACT

This research advances efforts to protect and enhance soil conditions within urban environments, an urgent priority for the European Union in pursuit of healthy soil (European Commission, 2023). It frames soil as interconnected with critical resources such as food and water in garden systems, enabling their co-evaluation through relevant drivers and pressures to promote long-term sustainability and resilience. Additionally, the research offers a framework and a set of indicators to assist urban planning practitioners and decision-makers in designing sustainable UFGs. This approach encourages integrated, cross-sectoral collaboration and moves beyond siloed perspectives, fostering more holistic urban development.

In the scientific context, the proposed research offers a solution to incorporate soil into the core of ecological nexuses (Hatfield et al., 2017; Lal et al., 2017). It develops a theoretical framework, establishes common research guidelines, and provides methodological support for the FWS nexus. This approach could be valuable for future studies aiming to apply the FWS nexus to other NbS systems, thereby enabling the monitoring and assessment of their sustainability performance.

1.6.1 Thesis structure

This thesis is organized into six chapters. Chapter 1 provides a general introduction to the background and research problem, followed by research aims and objectives.

Chapter 2 offers a literature review of the existing theoretical and methodological nexus framework for UFGs. In addition to an overview of the available methods, tools, and indicators for assessing UFGs, the chapter also presents arguments and suggestive pathways to incorporate soil into the current research paradigms.

Chapter 3 continues with the development of the food-water-soil nexus concept through ESs and EDSs lenses. It conceptualizes soil as a dynamic capital asset, which determines the flows of ES and EDS to contribute to human well-being in urban gardens, and how we could manage the feedback loops of human-nature interaction.

Chapter 4 grounds the framework through analysing gardener perceptions of ES and EDS, providing empirical data and insight into the case study of Nantes UFGs. Besides validating the methodological approach of the FWS nexus, findings from the chapter are utilized for the development of an assessment framework.

Chapter 5 provides details of the FWS assessment framework adapted from the participatory MESMIS methodology, including the indicator selection process and

the application of the index to the Nantes case study. It assessed the sustainability profiles, strengths, and weaknesses of the gardens.

Chapter 6 synthesizes the overarching findings from the preceding chapters. It discusses the strengths and limitations of the FWS framework and provides

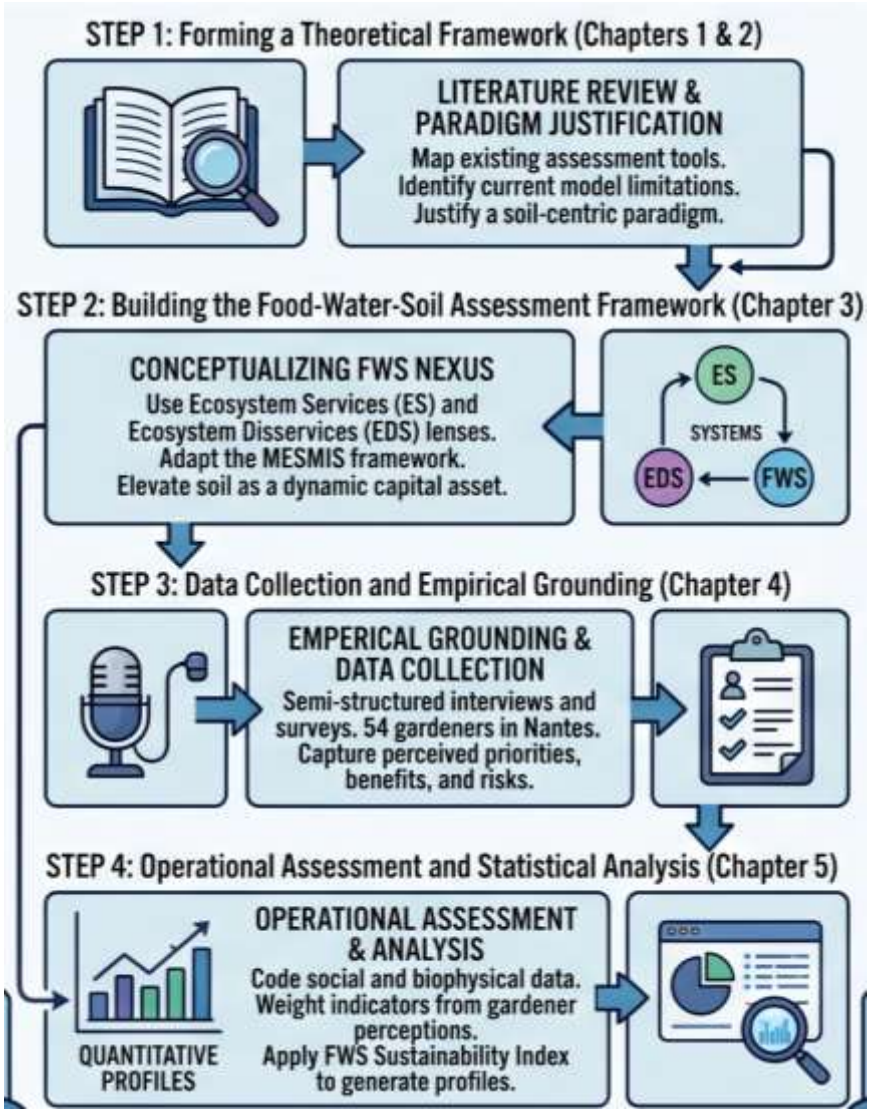

Figure 1.4. Master Methodological Flowchart

concrete implications and recommendations for future research, urban policy, and community practice.

2 MAPPING THE LANDSCAPE OF URBAN FOOD GARDEN INTEGRATED ASSESSMENT: A CRITICAL REVIEW

DISCLAIMER

A part of this chapter has been submitted as an opinion paper. It is currently under review in the journal *Earth: Environmental Sustainability*, under the title "*Untangling the Food-Water-Soil nexus through the lens of Ecosystem Services and Disservices in urban gardens*". The paper was authored by:

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Abstract

Urban food gardens (UFGs) are increasingly seen as key to urban sustainability, but the methods for evaluating their complex benefits and drawbacks are still disjointed. This systematic review charts and critically examines the various integrated assessment approaches for planning and evaluating UFGs. By adhering to PRISMA guidelines, 58 peer-reviewed articles were analyzed to map the dominant analytical methods. The analysis shows that the field is organized into five main methodological groups: (1) Quantitative Sustainability Assessment, (2) Spatial Planning & Optimization, (3) Systems & Nexus Modeling, (4) Socio-Ecological & Community Assessment, and (5) Empirical & Field-Based Studies. While material nexus (e.g. water-energy-food) is a popular high-level concept, most studies (60.3%) do not explicitly use it but other interconnections of non-material nexuses, revealing a gap between academic discourse and practical research. The discussion breaks down the inherent limitations of each group and identifies two main areas for future research: the need for better integration of different methodologies to connect quantitative and qualitative approaches, and the need to "re-ground" assessments in the dynamic dimension of soil—a vital yet consistently overlooked element of the urban food-energy-water nexus.

Keywords: *urban agriculture, nexus thinking, integrated assessment, social-ecological system.*

2.1 INTRODUCTION

The 21st century is marked by rapid urbanization, with most of the world's population now living in cities or semi-dense areas (Ehrlich et al., 2024). While this demographic shift drives economic growth, it also places unprecedented pressure on our urban systems, raising global concerns about food security, resource management, and climate resilience (Foley et al., 2005). In response, cities are actively pursuing more sustainable development pathways and are often seen as leaders in addressing climate change and fostering innovation for a resilient society. Among both traditional and modern approaches, urban edible green infrastructures (e.g. community gardens, allotments, and advanced rooftop farms) have become a vital strategy for promoting sustainable and resilient urban environments (Cabral et al., 2017b; De la Sota et al., 2019). Although these forms of agriculture have been tied to human existence, enhanced understanding of social-ecological systems has highlighted urban agriculture's intricate connections with city life and its interactions with water, energy, land use, and socioeconomic systems (Barthel et al., 2010). This interconnectedness means that any intervention can trigger cascading effects, resulting in both beneficial synergies and challenging trade-offs (Depietri, 2022; Zhang and MacKenzie, 2024).

Amid efforts to create more resilient and sustainable urban food systems, a new approach—centered on interactive and place-based research—is emerging across the European Union: the urban living laboratory for co-designing nature-based

solutions (NbS) (Lupp et al., 2020). These environments are not laboratories in the traditional sense. Rather, they are real-world spaces woven into the fabric of the city, providing a vibrant setting where diverse stakeholders can come together (e.g. researchers, local residents, municipal authorities, and private sector partners). Within these living laboratories, participants collaboratively design, test, and adapt innovations in urban agriculture, addressing challenges as they arise in urban contexts (Bulkeley et al., 2019; Ternell et al., 2024). What makes this paradigm particularly compelling is its departure from conventional, linear models of research and development. Instead, urban living laboratories foster a genuinely dynamic process of co-creation and social learning of various agriculture NbS, such as community gardens, green corridors, or rooftop gardens (Galdámez et al., 2025; Nunes et al., 2021). The European Union, through strategic initiatives under frameworks such as Horizon Europe, has actively championed the living lab model as a critical instrument for accelerating the agro-ecological transition. Programs like the "Mission 'A Soil Deal for Europe'" explicitly advocate for the establishment of urban living labs to address challenges of soil health and land use (Panagos et al., 2024), which are fundamental to the viability of urban farming. These initiatives recognize that the complexities of urban gardens—spanning spatial constraints, circular economy principles, and social equity—demand a multi-stakeholder and adaptive approach to innovation (Mumaw and Mata, 2022).

These complexities underscore a critical gap between its widespread promotion of urban agriculture and its effective, evidence-based implementation: the need for robust analytical tools and frameworks (Lehmann, 2018). Simple, ad-hoc, or single-issue approaches to planning invariably fall short of navigating the multifaceted dimensions of these systems. Suppose agroecological systems are to be successfully integrated into urban planning and policy; in that case, decision-makers should have access to systematic methods capable of assessing, modeling, and evaluating the intricate web of impacts stemming from various urban edible green infrastructure typologies and management strategies. Embracing such a comprehensive and analytical approach not only enables more strategic decision-making but also creates opportunities for meaningful progress toward a sustainable urban food system (Jahrl et al., 2021; Russo and Cirella, 2019).

While the 'nexus' concept has become a dominant paradigm in sustainability science (Ghodsvali et al., 2019), its application to the hyper-local, socially-embedded context of urban gardens remains contested.. Meaningful application of nexus thinking to edible urban gardens requires us to broaden our conceptual horizons. The complex reality of these spaces called for knowledge beyond the familiar water-food-energy (WEF) triad, embracing more nuanced frameworks such as the food-energy-waste-water (FEWW) nexus (Garcia et al., 2019)or soil biodiversity-climate change-society nexus (Eisenhauer et al., 2024). This broadening of scope is both necessary and challenging. The systems interacting

within a single community garden exemplify this complexity. These gardens are uniquely situated: they are intimately managed at the community level while simultaneously embedded within larger flows of food and materials. The factors that influence their success or failure are not confined to the biophysical, but encompass social, cultural, and political processes as well (Dorst et al., 2019; van der Jagt et al., 2019). As such, any effective nexus-based planning or assessment does not simply call for interdisciplinary insight; it demands profound inter- and transdisciplinary collaboration. Successful adaptation of such systems could significantly improve food security in urban environments, as evidenced by the Cuban urban agriculture system, which accounted for 60% of the country's demand for vegetables (Hanon, 2015).

The global interest in urban agriculture, particularly those initiatives linked to NbS, has seen a remarkable increase in recent years (Artmann and Sartison, 2018; Yan et al., 2022). Emerging themes related to cultivated urban areas often encompass the optimization of site selection, the assessment of environmental performance, and the evaluation of the benefits these systems provide. Among studies on urban agriculture, Rao *et al.* (2022) emphasize the lack of an integrated assessment that captures the multiple benefits arising from these practices; this gap significantly hampers the mainstreaming and formalization of urban agriculture across various sectors. Similarly, Kamali *et al*. (2025), while reviewing methods for selecting appropriate sites for urban food production, advocate for a greater integration of

social criteria within spatial models. This approach is particularly important for addressing inequities faced by vulnerable populations. Such integration is crucial for ensuring that urban agriculture not only thrives but also serves as a tool for social equity and environmental sustainability.

Thus, this review investigates the extent to which nexus thinking has been adopted and critically assesses the broader landscape of integrated assessment tools used in its place. We present a systematic review of the academic literature to identify, categorize, and synthesize the current landscape of assessment frameworks and tools designed to analyse the nexus of urban food gardens. In developing this review, we found academic discussion surrounding urban food production suffers from a critical lack of terminological precision. Broad terms like 'urban agriculture' often conflate vastly different models, from industrial, profit-driven vertical farms to non-profit, community-managed plots. This ambiguity makes a systematic analysis of assessment tools difficult, as methodologies designed for one model may be inappropriate for the other. For the purposes of this review, we establish a precise analytical category Urban Food Garden (UFG), which is defined as "***a public or private space within or on the fringe of urban boundaries, which is primarily used for growing vegetative plants for self-consumed food and other non-commercialized purposes***". This definition is crucial because it deliberately excludes profit-driven models, allowing our analysis to focus squarely on practices aligned with NbS and ecosystem service (ES) benefits. This delineation is crucial as

it deliberately excludes profit-driven urban agriculture. Commercial models frequently rely on environmental decoupling, technological intensification, and synthetic inputs to maximize yield, thereby compromising the complex, multi-trophic interactions requisite for NbS (Artmann and Sartison, 2018). Reliance on market mechanisms often introduces trade-offs that compromise biodiversity and soil health (Bliss, 2019). For the purposes of this study, UFGs are defined as managed urban spaces where food production is integrated with ecological and social functions, specifically prioritizing non-market ecosystem services over industrial-scale economic output. This definition distinguishes UFGs from commercial urban agriculture by emphasizing their role in local resilience rather than global commodity chains (Astuti et al., 2025). By excluding commercial models, the analysis focuses squarely on cultivated NbS that retain deep integration with local ecosystem processes..

Recognized UFG typologies include communal gardens, allotments, domestic gardens, urban forest gardens, and guerrilla gardens. Unlike the broader term 'edible green infrastructure,' which focuses on food provisioning (Russo et al., 2017), this conceptualization of the UFG emphasizes soil-bound, low-energy cultivation. Furthermore, as the FWS nexus represents a novel structural approach, limiting the scope to non-commercial UFGs ensures epistemological clarity. It allows for the rigorous mapping of physiological and hydrological cycles without the distorting influence of commercial optimization algorithms, thereby

isolating the mechanisms through which UFGs generate diverse cultural and regulating ecosystem services.

By adopting PRISMA guidelines (Page et al., 2021), this review aims to answer the following questions: 1) What are the nexus analytical/modelling approaches that assist urban food gardens planning and evaluation? 2) What are the key characteristics and limitations of these approaches? 3) What are the research gaps and future directions for developing integrated assessment tools? This literature review employs a quantitative and evidence-based approach, enabling the authors to identify nexus systems, their respective scales, methodological approaches, and the impact of these systems on planning and governance. Subsequently, this chapter aims to systematically map the current landscape of integrated assessment approaches to uncover the epistemological and practical tensions within existing models. Specifically, the objective is to evaluate how current frameworks account for, or overlook, the fundamental role of soil as a dynamic biological agent within the material nexus. By identifying these gaps, this review seeks to craft an integrative research approach to the urban food garden system, proposing alternative pathways and dialogue to understand nexus systems dynamics and interactions.

2.2 METHODS

2.2.1 Literature search design

In this paper, the focus was on original research works that present an integrated assessment on UFGs, linking multiple input factors or outcomes (i.e. social, environmental, and economic) for planning and optimizing UFGs. We applied a systematic literature review to examine integrative research methodologies for UFG systems, as described in Snyder (2019). While the UFG topic is not new, the application of multidimensional research approaches for such systems remains limited. Aiming at providing a synthesis lens and mapping out diverse methodological approaches, we defined three searching pillars that cover subject contexts, study methodological approaches, and study scale. Multiple related synonyms and word variants were included to ensure a comprehensive search. The three searching themes are:

i) The integrative concept: studies with an explicit focus on the interconnectedness

ii) The assessment concept: studies presenting a methodological approach for evaluation

iii) The subject concept: specific typologies of UFGs, excluding studies on general urban food systems or rural agriculture. Since researchers could use

different terms for UFGs or conduct assessments across multiple UFG systems, the keywords were expanded to include urban agriculture and peri-urban.

2.2.2 Search procedure and selection criteria

A search for academic literature was performed on Web of Science core collection on 12 March 2025, and one more time in August 2025 to enhance coverage and relevance. We use WOS as it is widely recognized as one of the most reliable sources of bibliographic data in the scientific community. The search was limited to peer-reviewed articles published in the English language until August 2025 to capture the modern evolution of the field. The search string was constructed using three conceptual themes, which the operator combined with “AND”. Terms within each thematic poctics were combined using the OR operator.

- Query 1: ("nexus" OR "interlinkage*" OR "interconnection*" OR "interdependen*" OR "trade-off*" OR "tradeoff*" OR "synerg*" OR "cross-sector*" OR "integrated approach" OR "co-benefit*")

- Query 2: ("assess*" OR "framework*" OR "evaluat*" OR "model*" OR "indicator*" OR "index" OR "indices" OR "tool*" OR "metric*" OR "analy*")

- Query 3 iii: ("urban agriculture" OR "urban farming" OR "allotment garden*" OR "community garden*" OR "edible green infrastructure" OR "backyard garden*" OR "kitchen garden*" OR "edible landscape*" OR "edible garden*" OR

"communal garden*" OR "edible green roof*" OR "school garden*" OR "edible botanic garden*" OR "edible green wall*" OR "edible forest garden*" OR "neighborhood garden*" OR "residential garden*" OR "guerrilla garden*")

Grey literature, encompassing municipal reports, non governmental organization assessments, and unverified policy documents, was deliberately excluded from the primary search corpus. This exclusion strategy isolates validated scientific consensus from preliminary or politically motivated urban planning heuristics, ensuring the evaluation rests on empirically tested researched work (Page et al., 2021). After excluding book chapters, conference proceedings, and meeting abstracts, the literature search yielded a total of 298 research publications. I performed an initial screening of the documents based on their title and abstracts, removing studies that are not related to the UFG concept or focus on a single issue or outcome. This resulted in 137 articles, all of which the authors were able to access the full text. A second round of screening based on reading of the full text reduced this number to 58 articles by removing conceptual papers that do not propose or apply a replicable assessment framework, model, or tool, purely descriptive studies (e.g. single-case ethnographies, historical analyses, policy commentaries) that do not present a replicable methodology for assessment purposes. Papers were selected if they satisfied the following criteria:

- Study subject: one or more specific typologies of UFGs.

- Study lens: adopt an integrated, nexus, or relational perspective, analyzing the trade-offs, synergies, co-benefits, or interconnections between multiple (e.g. social, environmental, economic) factors or outcomes.

- Study methodology: propose or apply a replicable assessment framework, model, or tool. This includes quantitative models (e.g. Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Multi-Criteria Decision Analysis (MCDA), optimization models, statistical models), empirical experiments, and structured qualitative frameworks designed for systematic assessment (e.g. a formal protocol for comparative case study analysis, a specific multi-criteria qualitative evaluation scheme).

The literature search was designed to capture a broad yet structurally relevant spectrum of integrated assessment tools. To ensure alignment with the overarching research, the search strings were calibrated to identify frameworks addressing the three primary axes of the FWS nexus. While this chapter maps the general landscape, the specific biophysical interdependencies are deconstructed in Chapter 3. Furthermore, the inclusion criteria favored studies exploring multi-functional outcomes, providing the foundational metrics for the multi-criteria index developed in Chapter 4. This structured approach ensures that the systemic gaps identified through this review are directly addressed in the empirical evaluation of the case studies presented in Chapter 5, bridging the divide between assessment theory and localized garden management.

2.2.3 Data Analysis

We conducted a comprehensive bibliometric analysis of the final dataset, which comprised 58 documents selected after meticulous screening. This analysis aimed

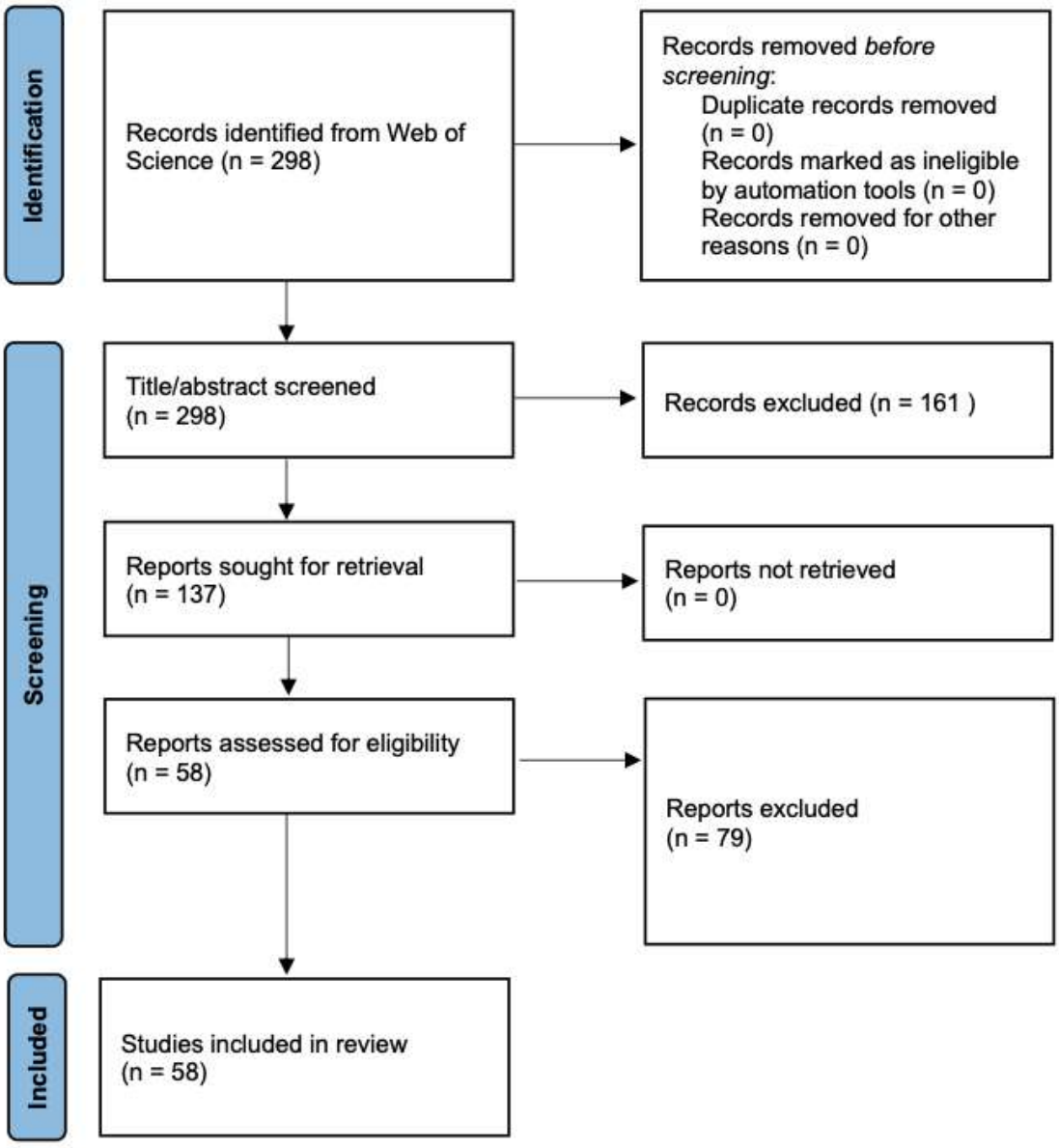

Figure 2.1. The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram for systematic review of UFGs

to systematically document the study subjects, scales, locations, methodological

approaches, input parameters, and key performance indicators associated with these works. In the subsequent stage, we undertook a detailed full-text analysis to explore the thematic groupings evident within the database, examining their evolution and the relationships between various research methods and their primary subjects of inquiry. Through this analysis, we identified common patterns and indicators frequently associated with specific methodological clusters.

This systematic classification establishes the empirical baseline necessary to deconstruct the interdependencies between divergent research approaches. By mapping these categories, the following sections aim to analyze the inherent limitations identified within the literature and bridge existing knowledge gaps. This diagnostic mapping facilitates a rigorous evaluation of the synergies between methodologies, providing the structural framework required to propose a refined, soil-centric research agenda in the subsequent discussion.

2.3 RESULTS AND ANALYSIS

2.3.1 Overview of analytical landscape and methodological flows

This review analysed 58 papers that met our specific criteria. Although research on city and regional-scale nexuses is still emerging, the earliest publication we found dates to 2015. That pioneering study introduced a water footprint model for urban agriculture, incorporating spatial analysis, an evapotranspiration model, and potential crop yield assessment. As shown in Figure 2.2, the range of nexus approaches for UFGs has expanded significantly over time. Despite the relatively small number of publications overall, those that

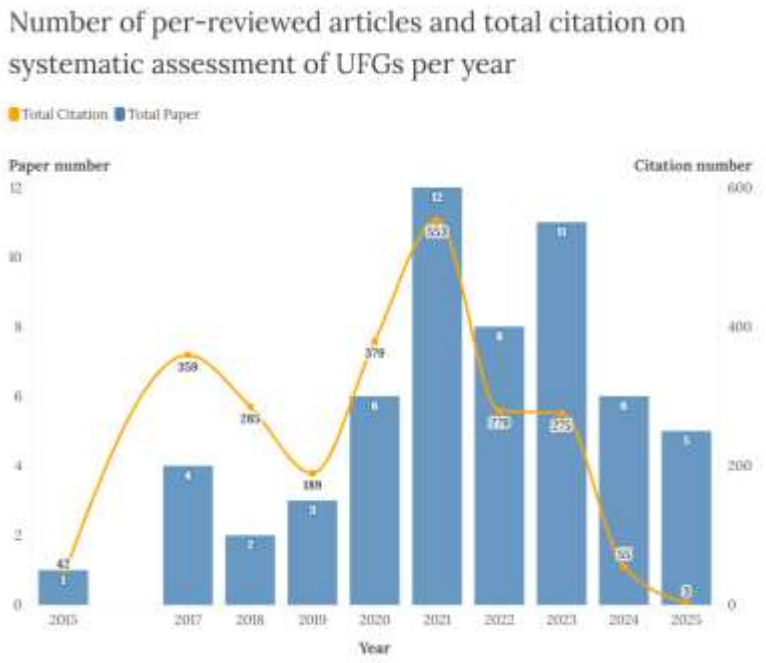

Figure 2.2. Academic publication overview on the integrated approaches for UFGs assessment (n=58)

involve integrated assessments of UFGs have garnered a notably high number of citations, around 42 per paper, underscoring their substantial influence within the academic community.

Among the analysed papers, 23 (39.7%) directly engaged with the core components of the WEF nexus, although many underwent conceptual evolution over time. The WEF nexus framework was explicitly employed in 10 studies (17.7%), primarily focusing on resource efficiency and the mechanics of circularity. Interestingly, an additional five studies (8.6%) implicitly integrated all three WEF components without explicitly naming the nexus, indicating a broader recognition of the integrated approach in studying these interconnected systems. Furthermore, eight studies expanded beyond the core WEF framework to incorporate other dimensions. These additional dimensions often represented a conceptual shift from a purely technocratic model to a socio-ecological perspective (e.g. *people* and *governance* dimensions) or toward a more comprehensive circular economy model (e.g. *waste* dimension). Researchers also adapted the core nexus idea to address pressing, context-specific urban challenges that extend beyond biophysical resource flows, encompassing factors such as *climate*, *transportation*, *land use*, and *economic* dimensions. Beyond WEF-related studies, most research, about 60.3%, or 35 papers, does not utilize an explicit, multi-resource nexus framework (i.e. WEF). Instead, these studies focus on understanding specific interconnections: the nexus between agricultural practices

and measurable outcomes (*practice-to-performance*), the nexus between people and the gardens themselves (*people-to-place*), or the nexus between a garden's location and a particular urban problem (*site-to-city*). These studies tend to adopt a more methodologically focused approach, often with a narrower scope and specific techniques. Despite this, they provide essential foundational knowledge on yields, social benefits, and environmental impacts.

We identified five main but interconnected methodological groups. Each group has its own key research questions, preferred tools, and typical ways of working. These groups include: (1) Quantitative Sustainability Assessment, (2) Spatial Planning & Optimization, (3) Systems & Nexus Modeling, (4) Socio-Ecological Assessment, and (5) Empirical & Field-Based Studies. The structural flow between these groups connects, along with their methods and the scales they work at, to follow a clear pathway outlined in Table 2.1 and discussed in the following sections**.**

Table 2.1. Overview of methodological clusters and research methods in UFGs

Methodological Cluster	**Research Method**	**Count**	**Reference**
Quantitative Sustainability Assessment	LCA	8	Caputo et al., 2021; Dorr et al., 2017; Imam et al., 2025; Meng et al., 2023; Sanjuan-Delmás et al., 2018; Stone et al., 2021; Toboso-Chavero et al., 2019; Zhen et al., 2020)

Methodological Cluster	Research Method	Count	Reference
	LCC	2	Dorr et al., 2017; Zhen et al., 2020
	Environment Footprinting & Emergy	2	McDougall et al., 2019; Stone et al., 2021
Spatial Planning & Optimization	GIS & Remote Sensing	18	Camacho-Caballero et al., 2024; Chen et al., 2023; Cumo et al., 2025; Fanfani et al., 2022; Kafle et al., 2023; Lin et al., 2025; Liu et al., 2022; Lowan-Trudeau et al., 2020; Lucertini and Di Giustino, 2021; M. Susana et al., 2023; Pedro et al., 2021; Small et al., 2023; Smith et al., 2021; Toboso-Chavero et al., 2023; Ustaoglu et al., 2021; Zambrano-Prado et al., 2021; Zhang et al., 2022; Zheng et al., 2025
	MCDA & AHP/Delphi	9	Babaei et al., 2024; Camacho-Caballero et al., 2024; Kong et al., 2025; M. Susana et al., 2023; Nie et al., 2024; Smith et al., 2021; Toboso-Chavero, Villalba, Gabarrell Durany, & Madrid-Lopez, 2021; Ustaoglu et al., 2021; Valencia, Qiu, et al., 2022
	Optimization Modelling	6	Kafle et al., 2023; Liu et al., 2022; M. Susana et al., 2023; Valencia, Zhang, et

Methodological Cluster	Research Method	Count	Reference
			al., 2022; Y. Zhang et al., 2022; Zheng et al., 2025
Systems & Nexus Modelling	Systems Modelling (SDM, ABM, MFA)	11	Elkamel et al., 2023; Gondhalekar & Ramsauer, 2017; Goodarzi et al., 2022; Huang & Chang, 2021; Jans-Singh et al., 2021; Pueyo-Ros et al., 2024; Valencia, Hossain, et al., 2022; Valencia, Zhang, et al., 2022; Weidner & Yang, 2020
Socio-Ecological & Community Assessment	Survey, semi-structured interview, statistical analysis	10	Babaei et al., 2024; Caputo et al., 2021; Kirby et al., 2021; Kong et al., 2025; Lowan-Trudeau et al., 2020; Nie et al., 2024; Rodríguez González et al., 2023; Siegner et al., 2020; Toboso-Chavero, Madrid-López, Durany, & Villalba, 2021; Valencia, Qiu, et al., 2022
Empirical & Field-Based Studies	Field Measurement and ES Evaluation	9	Caputo et al., 2023; Dennis & James, 2017; Dorr et al., 2023; Grard et al., 2018; Holt et al., 2017; Jha et al., 2023; Mulier, van de Ven, et al., 2022; Taylor, 2020; Wright et al., 2021

Note: Total label is higher than the number of analysed papers because a single paper often employs multiple methods. Further analysis is in section 2.3.3

Due to the high dimensionality of the indicators mapped in Figure 2.3, certain granular details may be restricted by the static format of the print version. To

ensure full accessibility and legibility, a detailed breakdown of these indicators, organized by their respective methodological clusters and functional themes, is provided in Appendix A (Table A.2.1). This table serves as a readable companion to the visual map, allowing for the cross-referencing of specific metrics across the five identified methodological families.

2.3.1.1 Quantitative Sustainability Assessment

This cluster encompasses studies that aim to develop objective, quantifiable metrics for assessing environmental and economic performance. It is based on the principle that sustainability can be measured, compared, and benchmarked. Central to this approach is LCA, which evaluates environmental impacts across various concerns such as global warming potential, eutrophication, and fossil fuel depletion (Dorr et al., 2017; Meng et al., 2023; Sanjuan-Delmás et al., 2018). LCA is often complemented with LCC to provide a parallel economic assessment (Dorr et al., 2017; Zhen et al., 2020), thereby enabling an eco-efficiency analysis for decision-makers. Additional methods employed within this cluster include Environmental Footprinting (e.g. carbon, water) and Energy Analysis, which quantify the total embodied energy of a system (McDougall et al., 2019). Primary inputs were detailed inventories of material and energy flows, meticulously catalogued for LCA. The reviewed papers consistently draw upon inputs from infrastructure materials, substrates, fertilizers, and energy consumption, as the process aims to create a comprehensive ledger of all resources extracted from the

economy and environment to support the production process of UFGs. Figure 2.3 illustrates common input parameters across five methodological clusters.

Research within this cluster generally adheres to a highly structured and linear methodology. Workflows typically start with establishing the system boundaries and the definition of the functional unit (e.g. “1kg of tomatoes produced.") This is followed by a comprehensive life cycle inventory phase, during which all material and energy inputs and outputs are meticulously documented. The final phase involves life cycle impact assessment, which translates the inventory data into environmental impact indicators. This systematic approach enables reliable comparisons between different systems, such as an integrated rooftop greenhouse versus a conventional one (Sanjuan-Delmás et al., 2018). Therefore, the methodological framework is frequently applied at the plot and building scales, where the well-defined boundaries of a single system (e.g. a rooftop farm) facilitate detailed inventory analysis. It can also be employed at a conceptual or multi-scale level to compare entire food systems, for example, contrasting large-scale conventional agriculture with small-scale local production (Stone et al., 2021).

2.3.1.2 Spatial Planning & Optimization

The Spatial Planning & Optimization cluster focuses on determining optimal locations and configurations for UFG interventions to maximize their benefits. Its

primary aim is to develop decision-support tools for urban planners, policymakers, and community organizers. The core tool utilized by the cluster is Geographic Information System (GIS), which facilitates mapping and analysis of spatial data alongside a broad spectrum of socio-economic information. GIS is typically combined with MCDA, a framework for assessing alternatives based on multiple, often conflicting, criteria such as social equity, environmental benefits, and economic costs. To operationalize MCDA, the Analytic Hierarchy Process (AHP) emerged as the dominant method for weight derivation among the reviewed studies (Ustaoglu et al., 2021). It should be noted that this prevalence reflects the current state of the reviewed literature rather than a methodological prescription. While other MCDA frameworks, such as the Weighted Sum Model for its computational simplicity, or outranking methods like ELECTRE and PROMETHEE for handling non-compensatory criteria, are established in general urban planning (Huang et al., 2011), they were notably absent or underrepresented in the context of the identified UFG-integrated assessments. The reliance on AHP in the reviewed pool suggests a preference for stakeholder-driven hierarchy over the complex pairwise outranking procedures characteristic of methods like ELECTRE Tri, which may be more suited for large-scale municipal infrastructure than for localized, community-led NbS interventions. For more complex applications, optimization algorithms are integrated to identify the most efficient spatial configurations that address multiple objectives simultaneously—such as reducing food deserts and urban heat islands (Zhang et al., 2022). The most frequent inputs for this cluster

are spatial representations: Land Use / Land Cover (appearing in 18 papers), Building Data (14 papers), and Infrastructure Networks (11 papers). These are frequently overlaid with socio-economic and demographic data, such as population density, income levels, and health vulnerability indicators.

Spatial analysis typically involves selecting specific criteria and gathering corresponding spatial data layers, such as income levels, vacant land inventories, and land surface temperatures. A key step in the process is assigning weights to these criteria, often through participatory expert rankings. The weighted layers are then overlaid within a GIS environment to generate a final suitability or priority map, helping to identify optimal locations for new UFG projects. Since the methods are designed for large-area analysis, this cluster operates mainly at community, neighborhood, city, and regional scales. Studies have employed this approach for strategic planning, such as identifying priority zones for community gardens across metropolitan areas (Smith et al., 2021) or planning for renewable energy communities (Cumo et al., 2025).

2.3.1.3 Systems & Nexus Modelling

This cluster seeks to understand and simulate the complex, dynamic, and non-linear interactions within urban resource systems. The literature clearly demonstrates a conceptual maturation of the nexus framework within the cluster; it moves beyond static assessments to explore feedback loops, trade-offs, and

systemic behaviour over time. While early applications focused on the core WEF triad, the nexus expanded to other resource nexuses to address key urban challenges. The inclusion of "Waste" to form a Food-Energy-Water-Waste nexus is a significant pattern, seen in studies such as Valencia *et al*. (2022) and Weidner & Yang (2020), which explicitly model waste streams (e.g. organic waste, wastewater) as resource inputs for UFGs, thus embedding the principle of a circular economy. A further evolution is the inclusion of the "People" dimension, as articulated by Caputo *et al*. (2021). This is a critical theoretical shift, arguing that social dynamics, behaviours, and well-being are not just outcomes but integral components of the nexus that influence resource flows. Adding the “People” dimension adds complexity, often requiring the integration of social survey data or agent-based models (Elkamel et al., 2023) to capture human decision-making. To reflect the behaviours of systems over time, this cluster often employs rates, stocks, and feedback parameters. The most common inputs are resource demand and supply data for water, energy, and food (appearing in 10-11 papers each), often as time series. These are supplemented by technology specifications (e.g. photovoltaic cell efficiency) and external drivers like climate change projections.

The primary methods within this cluster are simulation-based approaches. System Dynamics Modelling (SDM) is employed to capture feedback loops and the stock-and-flow dynamics, while Agent-Based Modelling (ABM) simulates the emergent, system-level consequences stemming from individual actors’ behaviours. The

process is inherently iterative, beginning with a conceptual mapping of the system's components and their interrelationships. This conceptual framework is subsequently translated into a quantitative simulation model, which is calibrated and validated using real-world data. The core of the analysis involves executing the model under various "what-if" scenarios (e.g. climate change projections or policy interventions) to explore potential systemic responses and trade-offs. Besides SDM and ABM, specialized models have been developed for more specific objectives and criteria. These include a co-simulation model developed by Jans-Singh *et al*. (2021) for detailed technical simulations of energy and growth dynamics of a building-integrated greenhouse. Meanwhile, Pueyo-Ros *et al*. (2024) developed a stochastic model to estimate UFGs' contribution to sustainability across a Mediterranean city. At the city and regional level, these methods were utilized to model urban metabolism and the interactions among extensive infrastructure systems (Valencia et al., 2022c). These simulation models could also integrate spatial data from GIS to provide context and inputs (Gondhalekar and Ramsauer, 2017), or LCA to assess the environmental impacts of different resource flow scenarios modelled within the system (Valencia et al., 2022a)

2.3.1.4 Socio-Ecological & Community Assessment

The Socio-Ecological & Community cluster systematically explores the human dimensions of UFGs, emphasizing the social, cultural, and political factors that influence its practices and outcomes. Research within this domain often prioritizes

understanding participant experiences and broader community impacts through a rigorous mixed-method approach, combining qualitative and quantitative techniques. Commonly employed tools include surveys, semi-structured interviews, and conducting case studies to collect quantitative data on motivations and perceived impacts (Kirby et al., 2021; Siegner et al., 2020). Frameworks such as ES and sustainable livelihoods frequently guide data collection and interpretation (Rodríguez González et al., 2023). Studies uniquely focus on human perceptions, values, and well-being when applying social science methodologies to measure concepts like general well-being, food security, and social cohesion. MDCA and AHP were also employed to determine indicators and their respective weights for the sustainability assessment of UFGs (Babaei et al., 2024; Nie et al., 2024). In this paradigm, an "indicator" is not just a material resource but can also be the social trust or traditional knowledge that enables a garden to function. Therefore, their main inputs are socio-economic demographics of participants (10 papers), participant motivations, stakeholder perceptions (often gathered via AHP/Delphi), and governance structures.

Researchers engaged in this cluster typically collaborate directly with community members and decision-makers to facilitate data collection. Data analysis involves thematic coding of qualitative data (Siegner et al., 2020) or statistical analysis of surveys, with findings interpreted through established social or ecological theories. Therefore, this cluster predominantly operates at the community and

neighborhood levels. However, certain studies extend these findings to conceptual or multi-scale frameworks by utilizing localized social dynamics to inform broader sustainability theories or regional policy models. For instance, Siegner et al. (2020) demonstrate how individual garden-scale data can be synthesized into a larger conceptual framework for urban agroecology. This capacity to bridge scales is further analyzed in Chapter 3 (Section 3.3), where we evaluate how community-derived values are integrated into the theoretical construction of a multi-dimensional nexus assessment.

2.3.1.5 Empirical & Field-based studies

Empirical and field-based studies are rooted in the scientific method, emphasizing direct observation and measurement. These studies frequently aim to generate primary, empirical evidence concerning the performance and impacts of UFGs under both real-world and controlled experimental conditions. For example, Dennis & James (2016) conducted on-site measurements of variables such as crop yield, water usage, soil quality, and biodiversity within operational gardens. Similarly, Taylor (2020) compared different management practices in controlled environments. Researchers also utilize citizen science, employing standardized protocols to collect data. The final outcomes typically involve measurements of on-the-ground processes, acting as proxies for ES. Instances include quantifying rainwater runoff reduction as a percentage metric for stormwater management (Wright et al., 2021) or measuring aphid removal rates as an indicator of pest

control efficiency by beneficial insects (Jha et al., 2023). These key performance indicators are distinctive because they represent direct, empirical measurements rather than modelled or perceived outcomes typical of other methodological approaches. A notable synergy in this approach is the application of GIS to analyse how surrounding landscape contexts influence the measured variables, thereby linking local processes to broader spatial patterns (Jha et al., 2023). The analysis depends heavily on statistical methods to assess the significance of observed results. This approach provides foundational data, such as crop yields and resource use efficiencies, that are often used to parameterize models in other research clusters. Its inputs are defined by what can be directly and physically measured on-site. The most common inputs are site and cultivated area, measured water consumption, and soil amendment application rates. Crucially, this is the only cluster where soil quality metrics appear as a significant input parameter (Taylor, 2020). This reflects a bottom-up approach to knowledge generation, where the analysis is built upon a foundation of primary, ground-truthed data. The inputs are not proxies for a larger system but are direct measurements of the system itself, albeit at a very localized scale.

The research process adheres to a traditional empirical workflow: forming hypotheses, designing experiments or data collection protocols, collecting and analysing primary data through statistical methods, and drawing evidence-based conclusions. This methodology is versatile, applicable across various scales, from

detailed, plot- or building-level studies (Grard et al., 2018) to multi-site analyses, such as evaluating the resource nexus among multiple farms within an urban area (Caputo et al., 2023; Mulier et al., 2022).

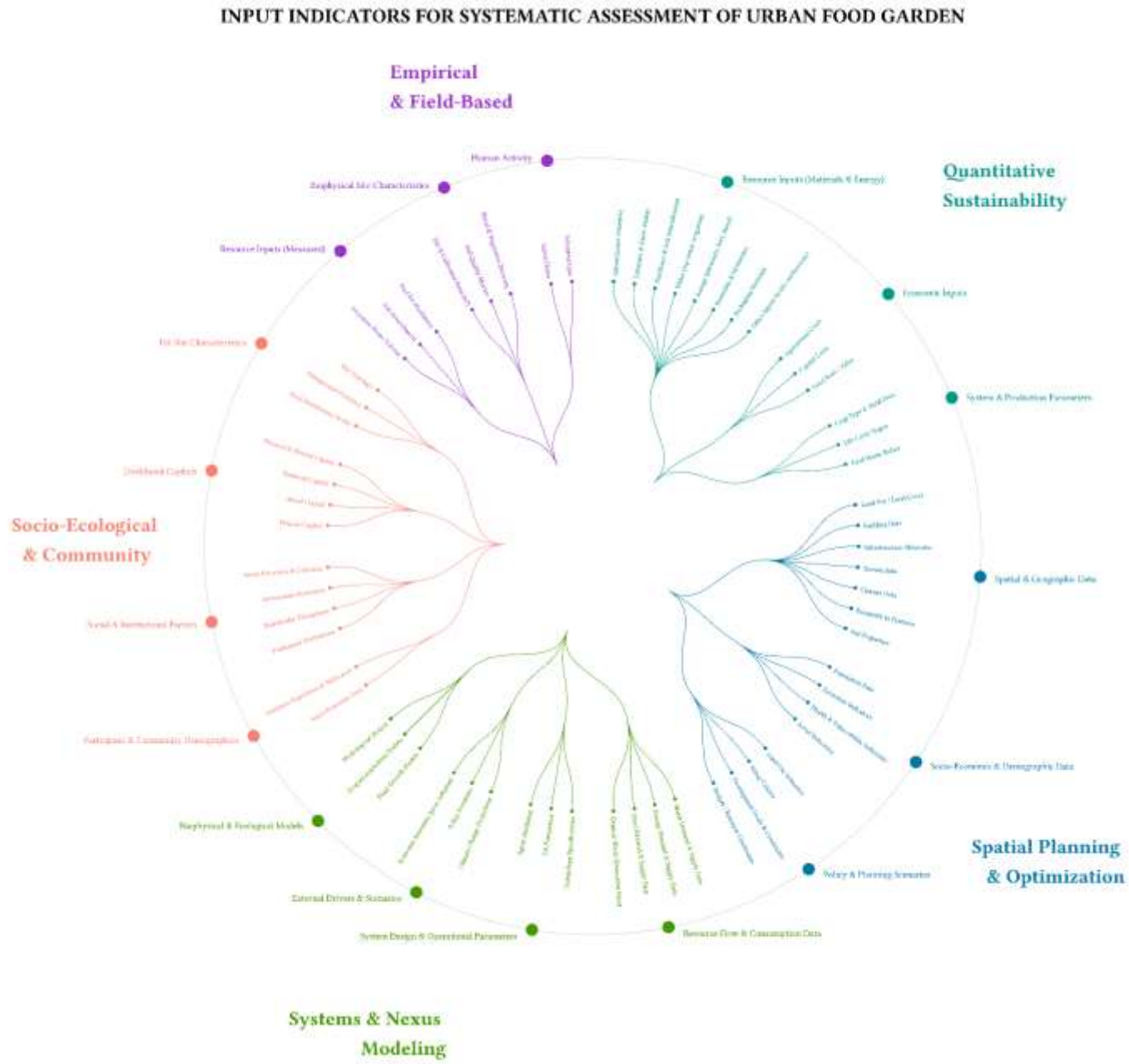

Figure 2.3. Indicators used in UFGs assessment (an interactive version can be assessed at https://kien-pham.com/UFGs)

2.3.2 Overlap in methodological cluster

2.3.2.1 Fundamental overlapping between clusters

While categorizing research into distinct methodological clusters offers a useful perspective, some individual papers in our database employed more than one scientific approach to develop a more holistic and problem-oriented understanding. Table 2.2 highlights seven studies out of the 58 analysed that primarily utilize a methodology from one cluster while extensively integrating key methods or frameworks from another. Notably, spatial assessments using GIS often incorporate a variety of input data, as demonstrated in Table 2.3, where GIS plays an essential role across different methodological clusters, serving as either a primary or secondary approach.

Table 2.2. Example of studies that employed core methods from a secondary cluster

Primary Cluster	**Secondary Cluster**	**Reference**	**Rationale for Overlap**
Spatial Planning & Optimization	Quantitative Sustainability Assessment	Liu et al., 2022	Uses LCA to quantify the environmental impacts of the spatially optimized WEF practices.

Primary Cluster	Secondary Cluster	Reference	Rationale for Overlap
Spatial Planning & Optimization	Systems & Nexus Modeling	Camacho-Caballero et al., 2024	Integrates ecosystem service and urban metabolism (a nexus concept) analysis into its spatial MCDA framework.
Spatial Planning & Optimization	Socio-Ecological Assessment	Lowan-Trudeau et al., 2020	Combines GIS mapping with statistical analysis of census data to explore the socio-demographic context of gardens.
Systems & Nexus Modeling	Quantitative Sustainability Assessment	Valencia, Hossain, et al., 2022	Integrates LCA principles into its system dynamics model to quantify decarbonization pathways.
Systems & Nexus Modeling	Spatial Planning & Optimization	Gondhalekar & Ramsauer, 2017	Uses detailed GIS and spatial statistics as the foundational input for its city-scale WEF nexus model.
Socio-Ecological Assessment	Quantitative Sustainability Assessment	Caputo et al., 2021	Combines a participatory social assessment with formal LCA and Material Flow Analysis in its "FEWP" nexus framework.
Empirical & Field-Based Studies	Spatial Planning & Optimization	Jha et al., 2023	Uses GIS to analyse how the surrounding landscape context (a spatial variable)

Primary Cluster	Secondary Cluster	Reference	Rationale for Overlap
			mediates the empirically measured ecosystem services.

2.3.2.2 Scenario applications across methodological clusters

Scenario methods were employed in 22 papers, representing 37.9% across various methodological clusters. Though widely used, these methods differ in logic and form but often share characteristics within clusters (Table 2.3). They were mainly employed in the System & Nexus Modelling and Spatial Planning & Optimization clusters.

The most common scenario type is the comparative scenario. For instance, in the Quantitative Sustainability Assessment cluster, Sanjuan-Delmás *et al*. (2018) compare an integrated rooftop greenhouse with a conventional one. Similarly, Empirical & Field-Based Studies use experimental treatments as micro-scenarios (e.g. Taylor (2020)'s soil management systems). In Spatial Planning & Optimization, scenarios are often normative, depicting desirable futures to guide policy, such as Fanfani *et al*. (2022)'s comparison of current land use with an agroecological vision. The Systems & Nexus Modelling cluster employs exploratory scenarios to navigate uncertainty, testing models against external forces like climate projections (e.g. RCP scenarios in Goodarzi *et al*. (2022) or socio-economic pathways (Elkamel et al., 2023). The goal is to find strategies robust across multiple

futures rather than predict specific outcomes. Finally, the Socio-Ecological cluster features participatory scenarios co-created with stakeholders, reflecting diverse values. For example, Kong *et al*. (2025) assess urban farms under different governance scenarios focused on social and political futures.

Table 2.3. Type of scenario analysis deployed in different methodological clusters

Methodological Cluster	**Papers Using Scenarios**	**Frequency within Cluster**	**Primary Scenario Type**
Systems & Nexus Modelling	9	81.80%	Exploratory Scenarios: Used to test the resilience of a system against external, uncontrollable forces (e.g. climate change projections, policy shocks, price inflation).
Spatial Planning & Optimization	7	38.90%	Normative Scenarios: Used to compare alternative, designed land-use plans or policy pathways to achieve a desirable future state.
Quantitative Sustainability Assessment	3	33.30%	Comparative Scenarios: Used to compare the performance of different technologies, management practices, or system configurations (e.g. integrated vs. conventional greenhouse).
Socio-Ecological & Community Assessment	2	20.00%	Participatory Scenarios: Used to represent different stakeholder-defined visions for the future or alternative governance structures.

Empirical & Field-Based Studies	1	11.10%	Treatment Scenarios: The comparison of different experimental treatments (e.g. soil management systems) can be understood as a form of micro-scenario analysis.

2.3.3 Scale of Analysis

The analysed papers were categorized by scale, from individual plots and buildings to city regions, as shown in Table 4. Methodologies such as Spatial Planning & Optimization primarily targeted mid to large scales, focusing on Community & Neighbourhood (45%) and City & Regional (40%) levels. In contrast, System & Nexus Modelling and Quantitative Sustainability Assessment are centred on micro-levels, with 42% and 33%, respectively.

The Plot and Building scale includes gardens, rooftop farms, or integrated building systems. Research here mainly involves controlled experiments aimed at understanding biophysical processes under specific conditions. This approach isolates variables to establish clear causal relationships. Empirical & Field Studies and Systems & Nexus Modelling dominate this scale, with models like the co-simulation of greenhouse and building energy balances (Jans-Singh et al., 2021), and LCA-based assessments such as Sanjuan-Delmás *et al*. (2018).

At the Community & Neighbourhood level, research shifts focus from biophysical processes to social dynamics, spatial access, and lived experiences. Social science methods like surveys and case studies are prevalent, exemplified by the Socio-Ecological & Community Assessment cluster (3 papers). Spatial Planning & Optimization (5 papers) examines the distribution of neighbourhood gardens, optimizing locations to meet community needs (e.g. Y. Zhang et al., 2022). Multi-site empirical studies (2 papers) analyse interactions between social and ecological variables across different gardens (Caputo et al., 2023; Jha et al., 2023)

The city and regional scale rely on models and large datasets to represent complex urban systems, as direct observation is impractical. This scale predominantly employs Spatial Planning & Optimization (8 papers) and Systems & Nexus Modelling (6 papers). GIS-based analyses are central here, as seen in city-wide suitability assessments (Ustaoglu et al., 2021) and ecosystem service mapping (M. Susana et al., 2023). System models simulate urban metabolism, exemplified by WEF nexus studies (Elkamel et al., 2023; Gondhalekar and Ramsauer, 2017). Other clusters are less frequent, often in multi-site studies, generalizing findings across cities.

Finally, the Conceptual/Multi-scale category is analytical rather than physical. It emphasizes developing and testing general frameworks, comparing systems across contexts, or synthesizing multi-scale findings. The Socio-Ecological & Community Assessment cluster (5 papers) here develops broad indicators (Babaei

et al., 2024) or compares social impacts internationally (Kirby et al., 2021). The Quantitative Sustainability Assessment (5 papers) compares entire food systems using methods like LCA (e.g. Stone et al., 2021). Spatial Planning & Optimization (3 papers) and Empirical studies (1 paper) contribute primarily when creating generalizable frameworks.

Table 2.4. Overview of the methodological clusters with the scale of analysis

Scale of Analysis	Quantitative Sustainability Assessment	Spatial Planning & Optimization	Systems & Nexus Modelling	Socio-Ecological & Community Assessment	Empirical & Field-Based Studies
Plot & Building	4 (33%)	-	5 (42%)	-	3 (25%)
Community & Neighbourhood	-	5 (45%)	1 (9%)	3 (27%)	2 (18%)
City & Regional	-	8 (40%)	6 (30%)	2 (10%)	4 (20%)
Conceptual / Multi-Scale	5 (36%)	3 (21%)	-	5 (36%)	1 (7%)

2.4 DISCUSSION

The results demonstrate a clear and logical alignment between the scale of inquiry and the chosen methodology, with quantitative, model-driven approaches dominating city- and regional-scale analyses, while qualitative and empirical methods provide deep, contextualized knowledge at the plot and community levels. This descriptive mapping, however, naturally gives rise to a more critical set of questions. Having established what methods are used and where, it is now necessary to explore what this methodological architecture implies for the production of knowledge in the field. The following discussion deconstructs the inherent limitations of each paradigm, explores the unstated assumptions and epistemological blind spots that shape their findings. By examining the tensions between quantification and justice, optimization and participation, and modelling and lived experience, this section seeks to illuminate not only the strengths of the current research but also the critical frontiers where a more integrated and reflexive science is urgently needed.

2.4.1 Critical reflection on the nexus approach in UFGs

While we framed this review through a nexus lens to capture the interconnectedness of UFGs initially, a majority of the studies themselves (60.3%) do not explicitly adopt a multi-component nexus framework like WEF. This finding

reveals a mismatch when applying the conventional nexus framework for the unique context of UFGs. The WEF nexus framework was originally conceptualized to address resource security challenges at large geopolitical scales, such as transboundary river basins or national resource strategies (Hoff, 2011; Palazzo et al., 2024). In contrast, a community garden operates at a hyper-local scale, often characterized by decentralized, informal, and socially mediated resource management. Resource flows from various sources are significantly challenged to capture in traditional nexus models (e.g. irrigation water may come from a municipal tap, or rainwater harvesting barrel, or a neighbour's hose). Therefore, the direct application of a large-scale framework to a neighbourhood-scale UFG can be an inappropriate analytical fit.

A significant challenge arises from the conventional epistemological orientation of the nexus framework, which is often perceived as a technocratic and resource-focused approach, as it emphasizes quantifiable biophysical flows and technical efficiency (Allouche, 2024). However, our research indicates that many of the UFG literature centres around the Socio-Ecological & Community Assessment cluster (see Table 2.1), emphasizing non-material benefits, often termed "incommensurable" by ecological economists (Satz et al., 2013), that resist easy measurement or comparison with a cubic meter of water or a kilowatt-hour of energy. The evolution of the nexus concept within our reviewed studies underscores this tension. The introduction of a "People" dimension to form a

FEWP (Food-Energy-Water-People) nexus by Caputo *et al*. (2021) aims to address this technocratic focus by recognizing social dynamics as essential components of the system. This marks a necessary shift from a purely technical analysis of resource flows towards a more socio-ecological understanding.

We would argue that future research should not abandon the nexus concept but rather apply it more critically and reflexively by moving beyond the WEF traid and embracing a more context-specific framework, such as the FWEP nexus mentioned above or WEFS (Water-Energy-Food-Soil) nexus that grounds the system in its material foundation. To illustrate, a conventional WEF analysis of an urban agricultural site measures volumetric water inputs, the caloric energy required for irrigation pumping, and the resulting crop yield, treating the planting medium as an inert black box. In contrast, a WEFS framework integrates the biogeochemical functions of the soil matrix as an active variable. For example, incorporating organic municipal compost (Soil) alters bulk density and increases soil organic carbon. This structural shift exponentially increases the water holding capacity of the pedosphere (Water), which consequently reduces the frequency of mechanical irrigation (Energy) while sustaining the physiological transpiration requirements for crop synthesis (Food). By explicitly defining the soil node, the nexus evolves into a localized ecological management tool capable of modeling biological resilience (Artioli et al., 2017; Newell et al., 2019).

Besides, Nexus is one tool among many. For questions centred on power, equity, or social change, it must be supplemented with other analytical frameworks, such as the social-ecological framework, to bridge the gap between the biophysical and social, ensuring that UFGs' assessments are socially just and meaningful.

2.4.2 Critical perspectives in integrated assessments of UFGs

In the Quantitative Sustainability Assessment cluster, LCA is a powerful tool aimed at creating an objective, comprehensive ledger of sustainability. While papers in our database often acknowledge limitations such as system boundary constraints and reliance on generic life cycle inventory databases, they rarely address the challenges posed by the unique nature of UFGs. A major issue is applying an industrial assessment tool to these non-industrial, complex systems. LCA was designed for standardized, linear production chains, but urban gardens are often polycultural and highly biodiverse, complicating the estimation of nutrient flows, water use, and yields for multiple intercropped species. Existing life cycle inventory databases lack the detailed data needed for such diverse systems, leading researchers to make simplifying assumptions that may not be accurate. Another significant limitation is LCA's inability to capture the social dimensions of community gardens. While it can quantify the carbon footprint of producing a kilogram of tomatoes, it cannot reflect social trust, intergenerational knowledge transfer, or cultural and aesthetic values. Emerging fields like Social Life Cycle

Assessment attempt to address this, but face philosophical challenges in creating a single impact unit for social and environmental values. As an ecological economist, Martinez-Alier (2002), argued, reducing incommensurable social benefits to a single ledger is a political and ethical act, not merely a technical one. Focusing only on measurable factors risks undervaluing the social benefits that often define urban agriculture's most cherished outcomes.

Meanwhile, the Spatial Planning & Optimization cluster offers valuable tools to bring order and strategic intent to urban agriculture development, but its pursuit of an "optimal" solution has notable limitations often understated in technical presentations. While studies like Smith *et al*. (2021) recognize the subjectivity in criteria weighting, a larger issue is that these solutions are optimal only within simplified models, not reflecting real-world complexity. Consequently, maps of "food deserts" or "high priority" areas are analytical constructs, not inherent features. More fundamentally, these models risk perpetuating inequality. Urban political ecology highlights that greening efforts can become gentrification catalysts, displacing communities they aim to help (Wolch et al., 2014). Current models cannot account for these socio-economic feedbacks, and their focus on efficiency may conflict with community-driven decisions, potentially disempowering local participation and fostering technocratic reasoning (read more in Kamali et al., 2025).

The Systems & Nexus Modelling cluster is defined by its holistic ambition to capture the complex, dynamic, and interconnected nature of urban systems. Its models provide a powerful "God's-eye view" of the city's metabolism. The most frequently acknowledged limitation in these papers is data availability and uncertainty. However, the deeper limitation is the risk of creating a "black box." As the models become more sophisticated, they can become opaque, making it difficult for stakeholders to understand or question their assumptions. This can create a false sense of predictive certainty about complex adaptive systems that are inherently unpredictable. As Meadows & Wright (2015) cautioned, we should not fall in love with our models; they are always simplifications. Besides, reliance on complex nexus models can alienate public discourse. Furthermore, the very act of defining the model's boundaries is an act of interpretation that shapes what is seen as important. By focusing on quantifiable resource flows in the WEF nexus, as many of the papers included in this review do, we risk overlooking other critical flows of knowledge, of social capital, of political power, which may be equally important in shaping the sustainability of urban systems.

In contrast to the lack of social dimension in LCA, Socio-Ecological and Community assessments often correct the technocratic biases of other paradigms by emphasizing the human aspects of UFGs. A common critique is that these findings lack statistical generalizability due to small, non-random samples (Cox, 2015). Another often unstated limitation is the tendency to overlook broader structural

constraints. Focusing on community gardeners' resilience and empowerment can unintentionally shift the burden of fixing a broken food system onto under-resourced communities, while masking the influence of larger forces like land markets, national policies, and systemic racism. This raises a fundamental sociological question: how much can grassroots action challenge powerful political and economic structures?

And last but not least, the Empirical & Field-Based Studies provide the primary, ground-truthed data upon which much of the other research relies. It is grounded in the scientific method of direct observation and measurement, seeking to produce objective, verifiable knowledge about the performance of urban agroecosystems. The primary and most frequently acknowledged limitation in these papers is the question of external validity. Findings from a neatly managed, replicated experimental plot, as in the work of Taylor (2020) on soil management, may not accurately reflect the messy, complex, and socially embedded reality of a real community garden, which is subject to variable management skills, fluctuating participation, and site-specific constraints. This tension becomes even more acute when the cluster turns its attention to assessing ES. While providing invaluable quantitative data, the empirical approach to ES in studies like Dennis & James (2017) and Jha *et al*. (2023) carries a series of unstated limitations that reflect a broader academic debate about the ES framework itself. Some of them include the simplification of the proxy and ecological reductionism, the utilitarian and

managerial worldview of the results in terms of "synergies and trade-offs" (e.g. Sylla et al., 2020) and the systemic neglect of ecosystem disservices[1] (Lyytimäki and Sipilä, 2009), and the struggles to capture the social co-production of ecosystem services.

2.4.3 Beyond the boundaries of methodological clusters

The previous analysis has broken down the landscape of UFGs research into five distinct methodological clusters, each characterized by its own internal logic, preferred tools, and inherent limitations. This categorization serves as a useful heuristic, while also highlighting that numerous studies have attempted to bridge the gap between these approaches by employing multiple core methodologies across different clusters. Building upon the reviewed literature and broader academic discussions, we consider the potential synergies, challenges, and philosophical implications of integrating these methodological clusters to advance a more holistic and influential science of UFGs.

A particularly promising and necessary integration involves combining the "*where*" aspect of Spatial Planning & Optimization with the "*for whom*" and "*how*" aspects

[1] Within the context of this dissertation, ecosystem disservices refers to the unintended negative consequences of urban gardening, such as nutrient leaching, soil contamination, or heightened water competition. which can compromise systemic resilience if left unmanaged. A comprehensive definition and theoretical deconstruction of ecosystem disservices, specifically regarding its role as a vital feedback signal within the pedosphere, is provided in Section 3.3.2.

of Socio-Ecological & Community Assessment. The former offers robust tools for land allocation, while the latter provides a nuanced understanding of community needs and values. The process could start with qualitative methods from the socio-ecological cluster, such as interviews, focus groups, and participatory mapping, to collaboratively identify community-defined criteria for successful and desirable garden locations. This approach departs from the expert-led criteria selection seen in studies such as Ustaoglu *et al*. (2021), emphasizing co-production of knowledge. These locally identified criteria could then become the direct inputs for an MCDA framework. In this case, the AHP method would be used as a tool to facilitate community deliberation on the relative importance of their values, moving beyond the extraction of preferences from predefined expert criteria. The resulting GIS-based suitability maps would serve not as final, authoritative solutions but as dynamic tools fostering ongoing community dialogue—acting as boundary objects that support participatory decision-making. This integrative approach directly addresses a key limitation of the spatial planning cluster: its tendency toward top-down, technocratic planning. By fostering collaboration between spatial planning and the community it serves, this method holds the promise of generating plans that are more likely to be embraced, effectively implemented, and sustainably maintained by the communities they aim to serve.

Secondly, integrating Empirical Field-Studies with Systems & Nexus Modelling could address the most significant weakness of the Systems & Nexus Modelling

cluster: the risk that its complex simulations are disconnected from the biophysical reality of urban farms. The Empirical & Field-Based Studies cluster provides the essential "ground-truthing" data needed to build, calibrate, and validate these models. For example, context-specific soil and nutrient data from Grard *et al*. (2018) can be used to parameterize and calibrate a top-down SDM or ABM model. The primary advantage is a noticeable increase in the credibility, accuracy, and local relevance of the systems models. It could support creating policy-support tools that decision-makers can trust, as the model's projections are not based on generic literature values but on measured data from their own city or region. However, the generation of high-quality, long-term empirical data is expensive, slow, and labour-intensive. A robust systems model requires years of calibration data, which conflicts with the short timelines of most academic and funding cycles. There is also a significant challenge in scaling up. How does one translate data from a few experimental plots into parameters that are representative of the vast heterogeneity of hundreds of gardens across a city? This is not just a technical problem of averaging but a conceptual one of dealing with complexity and diversity. Navigating this tension requires a careful and reflexive understanding of what each method can and cannot claim to know.

Finally, integrating quantitative and socio-ecological assessments (i.e., Quantitative Sustainability Assessment and Socio-Ecological & Community Assessment) is notably challenging. A genuinely integrated approach should not

simply append social indicators to a traditional LCA; it would start with socio-ecological inquiry. Using methods like interviews and participatory workshops, stakeholders would help define key social impact categories early on. Instead of relying on generic Social-LCA frameworks, the process would develop context-specific indicators for concepts such as community cohesion, food sovereignty, and cultural heritage. While this approach holds promise for a multi-dimensional sustainability assessment that addresses both technical efficiency and human values, it faces significant obstacles. Quantifying social impacts in a way that aligns with environmental metrics could dilute social critiques by the dominant technocratic paradigm. For instance, how do we measure a "unit of social cohesion" or ethically compare it to CO_2 emissions? A more honest approach, as suggested by some scholars, may be to resist full integration and instead present the social and environmental assessments as parallel, incommensurable narratives, forcing decision-makers to grapple with the trade-offs in a deliberative, rather than a purely technical, manner (Munda, 2004).

2.4.4 Managing the uncertainty across UFGs' assessments

In a complex domain like UFGs and other NbS, where biophysical and social dynamics intertwine, different research methods employ distinct strategies to navigate the limits of their knowledge. These approaches reflect core assumptions about what can be known and how. Empirical field studies, for example, rely on

statistical analysis, controlled experiments with replication, and multi-site studies to reduce statistical error and enhance the generalizability of their findings. Similarly, modelling approaches like LCA treat uncertainty as a technical challenge of data variability. Researchers working with LCA often use sensitivity analysis to test key assumptions and frame results through comparative scenarios, shifting the focus from absolute certainty to a more defensible comparative advantage.

When research aims to inform planning, it must grapple with the uncertainties of social values and future needs. To navigate subjective values, participatory methods like the AHP play a central role in systematically determining what defines a "good" outcome (Ustaoglu et al., 2021), treating this uncertainty as a question for social negotiation rather than technical calculation. To address an unknowable future, scenario-based planning helps design strategies that are robust across multiple possibilities (Fanfani et al., 2022), a common approach in Spatial Planning & Optimization and System & Nexus modelling.

Other methods embrace uncertainty as an inherent feature of the systems they study. Complex systems modelling, for instance, moves beyond prediction to explore possibilities. It uses stochastic simulations to generate a range of potential outcomes and exploratory scenarios to test for resilience (Pueyo-Ros et al., 2024). In parallel, qualitative and socio-ecological research addresses interpretive uncertainty — the trustworthiness of its findings. Rigor is established through triangulation of data sources, rich contextual detail ("thick description"), and

researcher reflexivity, aiming not for statistical generalizability but for "transferability" that allows others to assess the relevance of the findings to their own contexts (Siegner et al., 2020). This methodological pluralism provides a sophisticated toolkit for investigating urban agriculture, where different forms of uncertainty demand different approaches to produce credible and useful knowledge.

2.4.5 Re-grounding the methodologies with a soil dimension

Despite its foundational role in UFGs, soil dimension is under-theorized in the research landscape, often being a soil-based system. Our systematic review of 58 papers reveals that while 20 papers (34.5%) include a soil-related parameter, it is predominantly treated as a passive substrate or a "black box". Soil often appears as a static variable in spatial models, an abstracted item in life cycle assessments, or is absent from nexus simulations altogether. Authors agree with Lal (2017) that soil is not external to the WEF nexus but should be placed at its very centre, forming a WEFS nexus. We argue that integrating a dynamic soil dimension is a necessary corrective that can address the limitations inherent in current UA research by grounding abstract models in material reality. Integrating a sophisticated understanding of soil can bridge the current divide between its

empirical treatment as a living system and its abstraction in other research paradigms. Such integration offers direct pathways to enhance existing methodologies.

- Quantitative Sustainability Assessment: Current LCAs effectively track emissions from inputs like compost but largely overlook soil's critical capacity for carbon sequestration. Incorporating dynamic soil carbon models would account for practices that build soil organic matter, potentially reframing gardens from carbon sources to net sinks and offering a more holistic climate impact assessment.

- Spatial Planning & Optimization: For spatial planning, a soil-centric view is a matter of environmental justice. Models that treat urban land as a blank slate ignore the legacy of industrial contamination (McClintock, 2015). This persistent environmental toxicity, frequently characterized by elevated concentrations of heavy metals such as lead, cadmium, and arsenic, is disproportionately concentrated in low-income and minority communities (Jones et al., 2022). Integrating high-resolution soil contamination data is therefore necessary for creating planning tools that are not only efficient but also safe and equitable.

- Systems & Nexus Modelling: In nexus modelling, soil is the nexus—the dynamic interface where water, nutrient, and energy cycles converge.

Current WEF models often treat soil as a simple container, missing key feedback loops. A dynamic soil health module could simulate how practices like composting enhance soil organic matter and water-holding capacity, thereby reducing irrigation demands and improving system resilience. This approach positions soil as the central regulating node of the urban agroecosystem.

- Socio-Ecological Assessment: Soil provides a tangible, material anchor for abstract social concepts. Building on findings that practitioners consider "*soil health a central organizing principle*", methods like participatory soil health assessment can be used. This transforms soil from a simple biophysical parameter into a site for knowledge co-creation, grounding concepts like "*stewardship*" in the shared, material practice of community care.

2.4.6 Limitations of this study

This systematic review offers a structured overview of the field; however, its findings should be interpreted with awareness of certain methodological limitations. The following are some limitations that authors were able to identify. First, the review's scope was limited to the Web of Science core collection, which, while comprehensive, excludes potentially relevant literature from other databases, as well as grey literature. Additionally, the review was restricted to

peer-reviewed articles published in English, which may underrepresent research from non-Anglophone regions and omit important insights present in other languages or formats outside traditional academic journals. A pivotal definitional choice was the classification of UFGs as primarily non-commercial; this exclusionary criterion intentionally omitted studies on profit-oriented models (e.g. vertical farms). As a result, the findings and identified methodological clusters may not comprehensively reflect assessment tools used within this rapidly evolving sector of NbS.

Furthermore, the five methodological clusters proposed are analytical constructs devised by the author to bring together the body of literature. While this framework is useful, the boundaries between clusters are somewhat permeable, as evidenced by overlap analyses; some studies could logically fall into multiple categories. Therefore, this categorization represents one of many possible approaches to organizing the field, and readers should consider its tentative and heuristic nature.

2.5 CONCLUSION

In seeking to map the methodological landscape of nexus-based assessment for urban food gardens, this systematic review has addressed three central questions. Our analysis of 58 research papers reveals a field structured around five distinct, albeit interconnected, methodological clusters: Quantitative Sustainability

Assessment, Spatial Planning & Optimization, Systems & Nexus Modeling, Socio-Ecological & Community Assessment, and Empirical & Field-Based Studies.

Emerging from this analysis is a characterization of the field, defined by a tension between the quantitative, model-driven paradigms that dominate at the city scale and the qualitative, empirical approaches that provide deep, contextualized knowledge at the plot and community levels. This review suggests that while each cluster operates with a coherent internal logic and a specialized toolkit, their inherent limitations are profound, ranging from the reductionism of LCA in capturing complex social benefits to the risk of spatial models perpetuating injustice if not critically applied.

Looking forward, this work points toward two critical frontiers for future research. The first is the pressing need for greater methodological integration. The path forward appears to lie in intentionally building bridges between these paradigms — grounding abstract models with empirical data and humanizing quantitative assessments with participatory values. The second gap identified is the systemic underrepresentation of the soil dimension. Our findings suggest that re-grounding research by integrating dynamic soil processes, from carbon sequestration to contamination legacies, is essential for addressing the core limitations of current assessment paradigms. Ultimately, this review proposes the need for robust analytical tools to guide the planning of urban food gardens. Authors would like to point out that the most fruitful path lies in fostering a more integrated,

transdisciplinary, and materially-aware science — one capable of navigating the complex nexus of interactions not just between food, water, and energy, but between data and values, between models and communities, and between the city and the living ground upon which it is built.

CHAPTER 2 SUMMARY

- **Methodology**: PRISMA-guided systematic literature review of 58 peer-reviewed articles, utilizing bibliometric and full-text analysis.
- **Key Results**: Identified five main methodological clusters in current urban food garden assessments. The analysis revealed a critical "soil blind spot" in dominant resource nexuses (like Water-Energy-Food), establishing the theoretical necessity for a new FWS approach.

3 UNTANGLING THE FOOD-WATER-SOIL NEXUS

DISCLAIMER

A part of this chapter has been submitted as an opinion paper. It is currently under review in the journal *Earth: Environmental Sustainability*, under the title "*Untangling the Food-Water-Soil nexus through the lens of Ecosystem Services and Disservices in urban gardens*". The paper was authored by:

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Abstract

This chapter introduces the Food-Water-Soil (FWS) nexus as a novel conceptual framework tailored for the analysis of soil-based, low-energy urban systems, with a specific focus on urban food gardens (UFGs). Traditional nexus frameworks often marginalize the foundational role of ecosystems, particularly soil, treating it as a static variable rather than a dynamic capital asset. In contrast, the FWS nexus positions soil at the core of the system, mediating the interactions between water availability and food (biomass) production. We employ the dual lenses of Ecosystem Services (ES) and Ecosystem Disservices (EDS) to serve as the primary analytical tools for evaluating the tangible benefits and detriments that emerge from these nexus interactions. This approach moves beyond simple material flow analysis to capture the qualitative performance of the garden as a living, multifunctional system. The chapter systematically categorizes the diverse ES and EDS co-produced within UFGs, linking them directly to biophysical processes within the FWS nexus. Furthermore, we critically apply a management hierarchy to develop a robust framework for the adaptive governance of the FWS nexus. Finally, building on these conceptual foundations, we propose a practical, indicator-based FWS Sustainability Index, adapted from the MESMIS methodology, designed to operationalize the nexus approach and guide management decisions toward optimizing the net contribution of urban gardens to urban well-being and fostering long-term socio-ecological resilience.

Keywords: urban garden, ecosystem services, ecosystem disservices, food-water-soil nexus

3.1 INTRODUCTION

Current resource management paradigms, notably the WEF nexus (introduced in Chapter 1), have provided valuable frameworks for understanding systemic interdependencies. However, their applicability diminishes when examining soil-based, low-energy urban systems (Caputo et al., 2021), such as urban food gardens (UFGs). In these contexts, energy is often a minimal input, while soil is not merely a passive substrate but the foundational living infrastructure that mediates the system's core functions. The WEF nexus and its conceptual descendants frequently marginalize ecosystems, treating them either as an additional node, an endpoint for impact assessment (e.g. Ravar et al., 2020), or an external driver influencing adaptation strategies (e.g. Muthee et al., 2021). This under-theorization of soil's central, dynamic role represents a critical gap in nexus research (Hatfield et al., 2017; Lal et al., 2017).

To address this gap, we propose and develop the Food-Water-Soil (FWS) nexus as a more fitting conceptual framework for UFGs. This framework repositions soil as the central mediating component, a capital asset whose health governs the interactions between water availability and food (biomass) production. To analyze the performance of this nexus, we employ the dual lenses of Ecosystem Services (ES) and Ecosystem Disservices (EDS). ES refers to the direct and indirect benefits humans derive from ecosystems (IPBES, 2019; Millennium Ecosystem Assessment, 2005), a concept that has become central to valuing urban nature-based solutions

(NbS) for their contributions to citizen well-being (Bush and Doyon, 2019; Castellar et al., 2021; Puppim de Oliveira et al., 2022). While some frameworks have begun integrating ES to clarify policy trade-offs (Fürst et al., 2017), they often overlook the co-produced harms, or EDS. As human–ecosystem interactions inherently involve nuisances (Lyytimäki and Sipilä, 2009; Pereira et al., 2023), a comprehensive assessment requires an integrated view of both positive and negative outcomes.

The necessity of a soil-centric approach is increasingly recognized at the policy level, with initiatives like the "Mission 'A Soil Deal for Europe'" highlighting the urgency of addressing soil health challenges (Panagos et al., 2024), Such programs acknowledge that the success of cultivated NbS requires a multi-stakeholder, adaptive approach to innovation and management (Mumaw and Mata, 2022). The FWS nexus provides the holistic and transdisciplinary perspective needed to guide such an approach.

This chapter, therefore, systematically builds the case for the FWS nexus, progressing from theory to practice. First, we establish the conceptual basis of the FWS nexus and detail the core biophysical interactions that drive it. Second, using the analytical lenses of ES and EDS, we categorize the beneficial and detrimental outputs generated by these interactions. Third, we present a hierarchical framework for the adaptive management and governance of these outputs. Finally, to render this conceptual work operational, we introduce a novel FWS

Sustainability Index — an assessment framework adapted from the MESMIS methodology. It is designed to translate the complexities of the nexus into a practical tool for evaluating and improving the sustainability of urban gardens.

3.2 FOOD – WATER – SOIL INTERACTIONS

The FWS nexus does not operate on an idealized agricultural baseline. As Joimel et al. (2016) demonstrate, urban pedological networks exhibit altered physico-chemical architectures, specifically elevated pH, structural compaction, and legacy anthropogenic inputs. These characteristics fundamentally alter the Water-Soil interaction, reducing hydraulic conductivity and limiting pedological buffering capacity. Consequently, the biological output of this compromised system must be heavily engineered. Orsini et al. (2020) establish that modern urban agriculture overcomes these physical limitations through structural interventions designed to force multi-functionality, extracting high-density provisioning and regulating services from a constrained spatial footprint.

To evaluate how effectively these interventions extract services and build resilience, it is necessary to define what is meant by the 'performance' of the interaction vectors within the FWS assessment framework. In this context, performance transcends a simple measurement of agricultural yield; it denotes the operational efficiency, regulatory capacity, and ecological resilience of the interacting components. Specifically:

- The performance of **Soil-Plant** interactions refers to the capacity of the soil matrix to support robust root architecture, facilitate nutrient cycling, and sustain biological growth despite the urban stressors mentioned above.

- The performance of **Soil-Water** dynamics denotes the hydrological efficiency of the pedosphere. A high-performing interaction is defined by the soil's capacity to maximize the infiltration and retention of 'green water' (plant-available moisture) while acting as a structural sponge to buffer against extreme surface runoff and localized urban flooding.

- The performance of **Food-Water** interconnections is defined by the system's agronomic water-use efficiency (frequently conceptualized as 'more crop per drop'). It evaluates the system's ability to conver hydrological inputs into edible biomass through physiological transpiration, while actively employing management strategies to minimize non-productive evaporative losses from the soil surface.

3.2.1 Soil – Plant interactions

Soil serves as the fundamental medium for plant life, performing three critical functions. It provides physical anchorage for roots, offers a porous structure for

water and gas exchange between roots and the atmosphere, and hosts a biotic community that decomposes organic matter, recycles nutrients, and stores resources. The exchange of water and gases between roots and the external atmosphere is not direct; rather, it is facilitated through the dynamic movement within these discrete soil phases. It is therefore highly relevant to consider the soil's liquid phase, which encompasses both water and vital dissolved substances, as the primary medium for root uptake and nutrient transport.

The architecture of the soil, known as its structure, is paramount to these functions. This arrangement of soil particles dictates the nature of the pore space, which in turn governs the soil's ability to hold and transport the liquid and gaseous phases. (Bronick and Lal, 2005). Soils rich in organic matter are more likely to possess this optimal structure and, largely due to the essential binding effect that organic matter exerts upon the mineral phases of the soil matrix. This interaction is vital for stabilizing soil aggregates, consequently granting the system a greater capacity to store the plant-available liquid phase. (Huntington, 2020). This environment also fosters the biological breakdown of materials like plant litter and manure by bacteria and fungi, a process that drives decomposition and carbon sequestration (Mueller et al., 2024). Anthropogenic physical disturbances, notably mechanical tillage and sustained static loading, exert profound yet highly heterogeneous impacts on the soil matrix (Batey, 2009). The trajectory of structural degradation is not universal but strictly dictated by the localized

pedological baseline, encompassing texture, mineralogy, and inherent organic carbon saturation. While mechanical inversion in coarse textured sandy profiles primarily accelerates the oxidation of transient organic matter with negligible risk of surface sealing, the identical stress applied to fine textured soils, particularly those dominated by clays, precipitates rapid macro aggregation. In cohesive soils, the dispersion of primary particles initiates immediate surface crusting, elevates bulk density beyond the physiological thresholds of root penetration, and reduces the connected macroporosity essential for hydraulic conductivity and root respiration (Blanco-Canqui and Ruis, 2018). Soil compaction presents a significant physical barrier that can severely limit root growth (Cogger, 2005). Furthermore, erosion by wind or water strips away the nutrient-rich topsoil, diminishing the land's productivity.

Vegetation is not a passive inhabitant of the soil; it actively engineers its environment through the actions of its roots and the contribution of its litter. As roots navigate the soil, they influence the formation and turnover of soil aggregates, create channels or macropores, and modify the physical structure of their immediate surroundings. This root growth can exert mechanical stress, sometimes compact the soil, and reduce porosity in the immediate vicinity of the root. However, depending on the existing soil conditions, it can also increase porosity at the root surface (Mueller et al., 2024). This is a critical distinction: in well-structured soils, roots often follow paths of least resistance, growing into

existing large pores with minimal disturbance, whereas in compacted soils, they are forced to expend significant energy to physically displace the soil matrix. At a finer scale, roots release carbon-rich compounds (rhizodeposits) and extend fine root hairs that bind soil particles together, forming a cohesive layer known as a rhizosheath that stabilizes the soil structure (Materechera et al., 1992). This rhizosheath is a key adaptive trait, especially under drought conditions, as it maintains crucial contact between the root and soil, ensuring continued water uptake from a drying environment. The area around the roots, teeming with microbial life, further enhances this process. These microbial communities, which are more abundant and diverse in the rhizosphere, produce sticky "glues" like extracellular polysaccharides that adhere to soil particles, strengthening aggregation (Redmile-Gordon et al., 2014). This cycle completes as decaying roots disintegrate, contributing to the buildup of soil structure and the formation of persistent soil organic carbon (Mueller et al., 2024; Neurath et al., 2021). Research indicates that this belowground carbon input from roots is disproportionately important for building the most stable forms of soil carbon, as it is deposited directly within the mineral soil, where it can be protected from rapid decomposition (Costa et al., 2018).

Aboveground plant litter is another crucial link between plants and soil, playing a primary role in shaping the physical structure of the topsoil (Ponge, 2003). This structure emerges from the interplay between vegetation and soil biota,

particularly the burrowing and fragmenting activity of soil fauna. The decomposition of litter releases nutrients, boosts the soil's capacity to hold onto them, and increases its water-holding capacity (Frouz, 2024; Six et al., 2004). The long-term result of these decomposition processes gives rise to distinct humus forms (e.g. Mull, Moder, and Mor), which serve as visible indicators of the ecosystem's functional state, reflecting the speed of nutrient cycling and the dominant decomposer communities. In many urban farm and garden settings, where natural litterfall is limited, materials like mulch, wood chips, and compost are often added to fulfil this essential role.

While these soil-plant interactions are universal, they face unique pressures in urban environments:

- *Soil Compaction*: Urban soils are frequently compacted from construction and traffic, which destroys pore space, limits water infiltration, and creates a physical barrier that can stunt root systems, leading to shorter, thicker roots with fewer lateral branches (Alessa and Earnhart, 2000).

- *Contamination*: Geogenic origins, industrial activities, lead-based paint, and leaded gasoline have left many urban soils contaminated with heavy metals, particularly lead. These contaminants pose health

risks through direct ingestion of soil or consumption of produce grown in it (Bechet et al., 2018; Jean-Soro et al., 2015; Paltseva et al., 2022).

- *Urban Heat Island (UHI) Effect*: The prevalence of heat-absorbing surfaces like asphalt and concrete raises ambient temperatures, which in turn increases the rate of evaporation from soil, depleting moisture more rapidly and placing additional stress on plants (Zipper et al., 2017).

These stressors often create a negative feedback loop: compaction and heat lead to poor plant growth, which means less organic matter is returned to the soil, preventing the natural rebuilding of the soil structure that would otherwise help mitigate these very issues. Management strategies in urban gardens, therefore, must focus on actively breaking this cycle. In cases of severe contamination, this involves constructing raised beds filled with 'Technosols' (engineered soils constructed from recycled urban organics rather than imported natural topsoil), incorporating large amounts of compost to rebuild structure, and adopting practices like no-tillage and cover cropping to protect and continuously build soil health (van Es and Magdoff, 2009). For the purposes of this assessment framework, soil health is formally defined as a complex, multi-attribute characteristic that encompasses the optimal integration of physical, chemical, and biological properties (Séré et al., 2024). Rather than viewing soil as a static medium, this definition establishes soil health as the continued capacity of the

pedosphere to function as a vital, living ecosystem capable of mediating the water cycle, sustaining plant growth, and buffering against urban environmental stress.

The most effective strategy for improving water dynamics in urban soils is to increase soil organic matter. Adding amendments like compost directly counteracts compaction by lowering bulk density and rebuilding soil structure (Frouz, 2024; Six et al., 2004). Rather than acting merely as a simple hydrophilic sponge, organic matter functions as a dynamic structural agent due to its amphiphilic nature, meaning it possesses both hydrophilic and hydrophobic functional groups. While the hydrophilic fragments actively interact with the soil's liquid phase to enhance moisture retention, the hydrophobic components play a vital role in binding with soil mineral surfaces and other organic molecules to form and stabilize structural aggregates. This combined structural stabilization creates a robust network of pores that simultaneously improves infiltration and exponentially increases the soil's overall water-holding capacity (Huntington, 2020). According to the USDA, a 1% increase in soil organic matter can help an acre of soil hold up to 20,000 additional gallons of water (Keller and Handler, 2024).

3.2.2 Soil – Water Dynamics

The principles of water balance in UFGs mirror those in other urban green spaces and agricultural settings. The system gains water through precipitation and

irrigation and loses it via infiltration into the soil, surface runoff, and evapotranspiration. This "green water", or the moisture held within the soil profile for plant use, is sometimes supplemented by stored water from rain barrels or tanks. While tap water and harvested rainwater are the primary irrigation sources for UFGs, some research highlights the use of greywater from kitchens and bathrooms, particularly in arid regions facing water scarcity (Al-Ismaili et al., 2017; Faruqui and Al-Jayyousi, 2002).

Water is more than just a resource for hydration; it is a dynamic agent within the soil. It facilitates the transport of nutrients to roots and serves as the medium for essential chemical and biological reactions. In this role, soil moisture acts as a critical nexus, linking hydrological cycles with biogeochemical processes and mediating the interactions between climate, soil, and plant life. However, excessive water movement through the soil profile can be detrimental, leading to the leaching of fertilizers and reducing their availability to plants.

The broader urban environment significantly alters this natural water balance. Across much of the city, severe soil compaction, often a consequence of construction, surface sealing, and heavy traffic, destroys the soil's porous structure (van Es and Magdoff, 2009). Studies have shown that compaction from construction can decrease infiltration rates by 70% to 99% (Gregory et al., 2006), turning these general urban areas into surfaces that shed water rather than absorb it. This not only increases stormwater runoff but also prevents rainwater from

replenishing moisture deep in the root zone, making plants more susceptible to drought (Bronick and Lal, 2005). However, it is critical to distinguish this degraded urban matrix from the soils within UFGs. UFG soils are frequently preserved, deliberately cultivated, and amended, allowing them to retain a highly functional porous structure. Rather than suffering from direct construction compaction, the water balance of these preserved garden soils is altered precisely because they function as highly permeable islands within a sealed cityscape. Because they remain unsealed, UFGs act as preferential infiltration sinks, frequently receiving concentrated stormwater runoff from adjacent impervious roadways and rooftops. Furthermore, even when the internal soil structure is well-preserved, the water dynamics of UFGs are still heavily compounded by the broader UHI effect (mentioned in the previous section 3.3.1), which accelerates evaporation and increases the overall water demand of garden plants.

Stormwater runoff from impervious surfaces (e.g. roadways, parking infrastructure, and rooftops) frequently serves as a primary, unmonitored hydrological input. Because urban food gardens are often situated in topographic depressions or deliberately lack structural barriers to maximize their utility as NbS for localized flood mitigation, they act as preferential infiltration sinks for the surrounding urban watershed (Corrêa et al., 2022). This runoff operates as a concentrated vector, transporting heavy metals such as lead (Pb), zinc (Zn), and copper (Cu) originating from brake pad friction, tire wear, and the degradation of

galvanized building materials (Guo et al., 2020). However, it must be explicitly underlined that the pollutant contents within this non-point source runoff water are generally much lower than those found in soils affected by direct point-source pollution. While the immediate concentrations of trace elements in the water are comparatively low, the fundamental concern is chronic exposure; as the garden acts as a continuous infiltration sink, these contaminants can gradually accumulate within the soil matrix over time, eventually posing potential health risks (Tom et al., 2014). The use of untreated greywater, while a good conservation strategy, also carries risks (Shqerat and Al-Tabbal, 2025). Long-term application can lead to the buildup of salts and sodium from detergents, increasing soil salinity and sodicity (Rahman et al., 2022). High sodicity is particularly damaging, as it can destroy soil structure, clog pores, and create an impermeable surface layer that prevents water infiltration (Al-Hamaiedeh and Bino, 2010). Greywater may also contain pathogens, though the risk is lower than with blackwater.

A study from Lin *et al.* (2018) demonstrates that foundational improvement in soil health (Section 3.2.1 with reference to the study of Séréet al, (2024)) should be paired with water-wise practices to improve the soil-water positive feedback loop:

- *Mulching*: Applying a layer of organic material like wood chips or straw to the soil surface insulates the soil, reduces evaporation, and suppresses weeds that compete for water.

- *Efficient Irrigation*: Using drip irrigation delivers water slowly and directly to the root zone, minimizing losses to evaporation and runoff. This method can reduce water use by 20% to 50% compared to overhead sprinklers (Ignaciuk et al., 2015). Watering deeply but infrequently also encourages plants to develop deeper, more resilient root systems.

- *Raised Beds*: For sites with severe contamination or compaction, raised beds filled with a high-quality engineered soil mix of compost and other materials offer a practical solution (Kessler, 2013; Le Guern et al., 2018). However, these contained systems often dry out faster and require more frequent watering.

-

3.2.3 Food – Water Interconnections

For crops, a steady supply of water is indispensable. It fuels essential metabolic processes and drives evaporative cooling through transpiration, a function that can moderate the local microclimate (Lin et al., 2018a). This cooling service becomes increasingly vital in urban gardens, where rising ambient temperatures intensify water demand. Effective vegetation management is therefore key to conserving this precious resource by influencing plot-level factors like surface temperature and evapotranspiration rates to preserve soil moisture (Lin, 2010). Strategic planting designs, such as increasing the canopy coverage and structural diversity of crops, can significantly improve water retention within the garden's micro-ecosystem. Additionally, applying ground covers like mulch or straw is a powerful technique. These materials shield the soil from wind and water erosion and dramatically cut evaporation rates. This practice directly boosts water use efficiency (i.e. the amount of yield produced per unit of water consumed) and can ultimately lead to greater harvests (Wang et al., 2021).

Plants are not passive water consumers; they actively regulate their use through opening and closing stomata, the microscopic pores on leaves (Pirasteh-Anosheh et al., 2016). Low water availability would trigger the stomatal closure, which reduces water loss from transpiration. However, this process also limits the intake

of carbon dioxide, slowing photosynthesis and potentially reducing growth and final yield. Different vegetable species exhibit distinct strategies for managing this trade-off. Under drought, snap beans, for example, may increase their stomatal density, while green peas show little change (Nemeskéri and Helyes, 2019). Tomatoes, which are highly sensitive to drought, respond acutely by altering both the size and number of their stomata. If water stress persists, plants may resort to more drastic measures, such as shedding older leaves or producing smaller new ones to reduce their total leaf area and overall water demand.

A key goal in sustainable agriculture is to improve water use efficiency, effectively producing "more crop per drop". In a garden setting, water use efficiency is enhanced by minimizing non-productive water loss (evaporation from the soil) and maximizing productive water use (transpiration by the plant) (Pollard et al., 2018). Practices like mulching and drip irrigation are highly effective because they target evaporation (discussed in previous sections). A meta-analysis confirmed that mulching significantly increases both crop yield and water use efficiency, with some studies showing gains of over 20% and 30%, respectively (Li et al., 2025). Interestingly, the relationship between water and food quality is not always linear. While severe drought is damaging, mild and controlled water stress can sometimes trigger physiological responses in certain crops that concentrate sugars, organic acids, and beneficial compounds like antioxidants. This can result in produce with more intense flavour and enhanced nutritional value, though

often at the cost of slightly reduced size or total yield (Jin et al., 2023; Naeem, 2025).

A resilient urban garden begins with smart plant selection and design. Below are some recommendations for improving the Food-Water nexus in UFGs:

- *Drought-Tolerant Crops*: Vegetables like pole beans, Swiss chard, eggplant, hot peppers, and certain varieties of tomatoes and squash are excellent choices. They often possess adaptive traits like deep root systems that can access more soil moisture. Amaranth and chickpeas are also exceptionally resilient. Conversely, water-intensive cool-season crops such as most brassicas (broccoli, cauliflower), lettuce, and celery are best avoided during peak summer heat.

- *Planting Design*: Arranging plants in dense blocks rather than traditional single rows allows their leaves to touch as they mature. This creates a "living mulch" that shades the soil, suppresses weeds, and reduces evaporation. Selecting compact "bush" or "determinate" varieties of plants like tomatoes and squash further enhances this effect (UC Agriculture and Natural Resources, n.d.).

- *Efficient Irrigation*: The most effective watering method is to irrigate deeply but infrequently. This encourages plants to develop deep, robust root systems that are less vulnerable to surface drying. As discussed

previously, Drip irrigation can reduce water use by up to 50% compared to overhead sprinklers by minimizing evaporation and runoff (Ignaciuk et al., 2015).

3.3 FWS NEXUS THROUGH THE LENS OF ES AND EDS

A crucial insight from ecological economics is that ecosystem services do not flow directly and passively from this natural capital to benefit people. Instead, both services and disservices are co-produced through the dynamic interaction between the cultivated nature capital (in this dissertation, it is viewed as urban

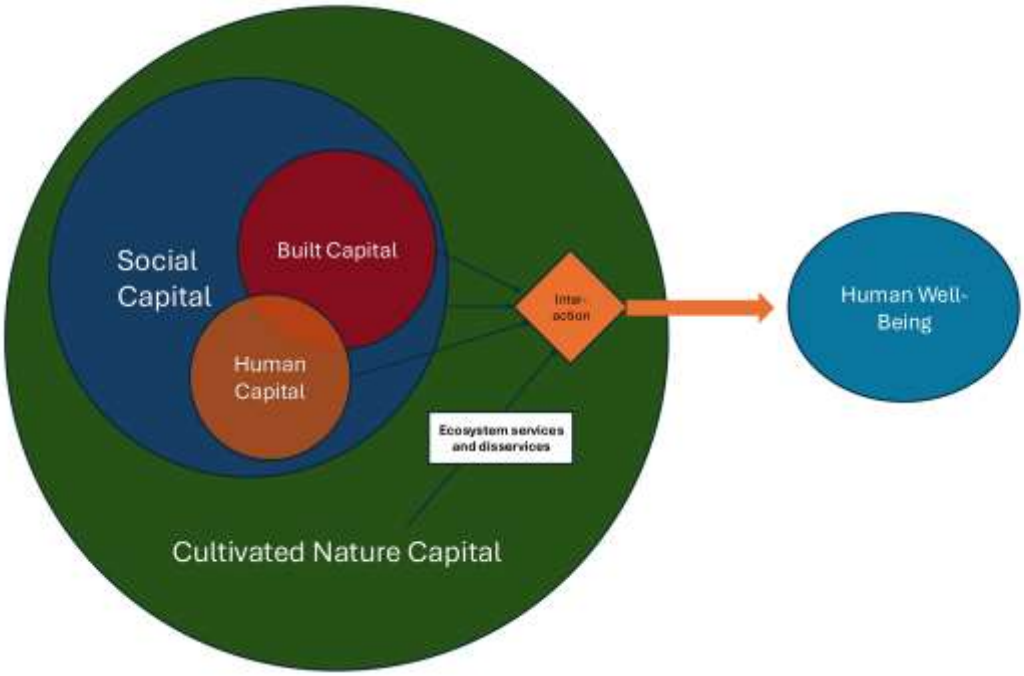

Figure 3.1. Interactions between nature capital and social capital affecting human well-being. Modified from Costanza et al., (2014).

gardens) and the other three capital stocks: social, human, and built. **Figure 3.1** establishes the key assets and actors—the four capitals—involved in this co-production (Costanza et al., 2014).

Let us consider the provisioning of food. The natural capital of urban gardens (i.e. soil, biodiversity, and climatic conditions) holds the potential to generate produce. This potential is only realized through the application of human capital (a gardener's knowledge and physical labour), which is aided by built capital (tools, irrigation systems, raised beds), and often structured by social capital (community garden rules, shared knowledge networks, and trust among members). The resulting harvest is a co-produced ecosystem service. Conversely, the very same interactions can generate ecosystem disservices. A gardener's lack of knowledge (human capital) combined with an overreliance on external inputs (built capital) can deplete soil organic matter, resulting in nutrient runoff and pollution of local waterways.

In contrast, a successful garden that enhances well-being can build social capital (stronger community ties) and human capital (new gardening skills). Thus, the ultimate contribution of the urban gardens to human well-being is the net outcome of these complex, co-produced services and disservices, which are mediated by the constant interplay of all four forms of capital. It thus becomes clear that ESs and EDSs are not an 'add-on' but rather the enabling and disabling features that define the nexus system's potential and its limits. ESs and EDSs emerge at the dynamic interface between the managed ecology of an urban food garden and the surrounding urban social system (Gómez-Baggethun and Barton,

2013), and represent the ultimate locus of interaction among the food, water, and soil dimensions of this nexus.

The ES-centric framework, proposed by Sambo *et al.* (2024), represents a significant step in centring ecosystems within the WEF nexus. It clarifies the complex interactions among multiple nexus sectors, as well as the pressures and responses of WEF to the ecosystem processes and functions that deliver their services. However, this framework neither offers the integration of the EDSs nor does it contain the soil dimension. Thus, the author adopted the framework and modified it to express the interdependence between the FWS nexus and the ESs and EDSs that are generated. Figure 3.2 illustrates the FWS nexus as a continuous socio-ecological feedback loop utilizing an ES/EDS cascade model. In this cascade model, the cycle begins with the *Ecosystem Structure* (dynamic soil and water properties), which drives biophysical *Functions* (e.g., plants' evapotranspiration or carbon accumulation). When intersecting with human needs, these functions manifest as *Ecosystem Services* (e.g., biomass yields, air purification) or *Ecosystem Disservices* (e.g., toxic dust, pest outbreaks). Crucially, these outputs are not static endpoints; they are evaluated through societal *Values*. For example, experiencing the disservice of insect bites prompts communities to re-evaluate the land as a public health liability, triggering adaptive Responses, ranging from localized gardener interventions (e.g., applying pesticides) to municipal policies (e.g., new regulations). These management responses loop back to physically alter the

baseline *Ecosystem Structure* for the next cycle. Ultimately, Figure 3.2 demonstrates that FWS nexus management is an ongoing, adaptive dialogue between ecological functions and urban governance, rather than a linear extraction of resources.

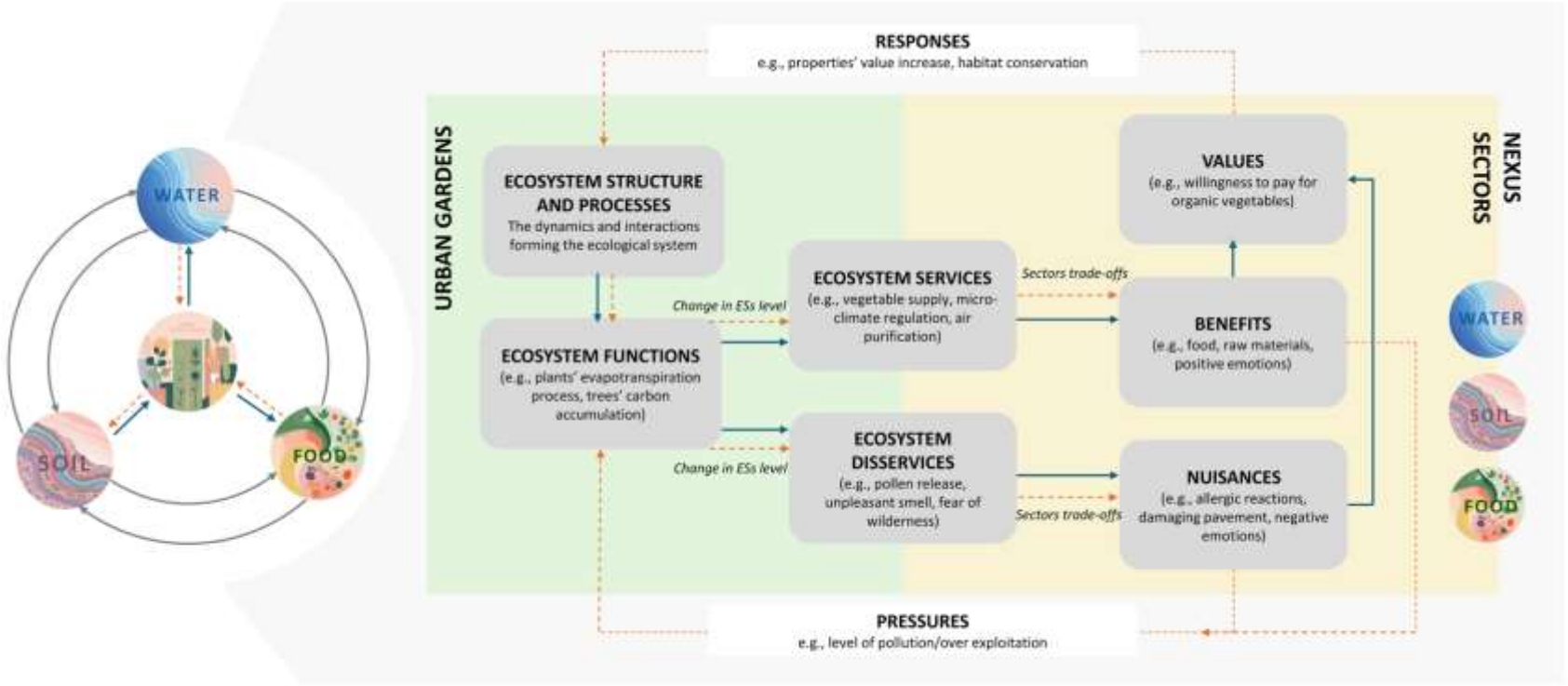

Figure 3.2. Integrating the ESs and EDSs model in the FWS nexus framework. Adapted from Sambo et al., 2024

E f

The intention of clarifying the FWS framework through the ES and EDS lenses in this dissertation is rooted in the dynamic and systemic perspective. Quantitative assessments, such as material flow analysis, often work best with resources that are easily quantified in standardized units (e.g. cubic meters of water, tonnes of grain, gigajoules of energy). Soil, however, defies such straightforward accounting. While soil mass can erode and be transported (as in material flow), this represents a system degradation rather than a managed resource flow. The resource we aim to manage is not soil mass, but its functional capacity. To accurately evaluate this, a distinction must be made between 'soil quality' and 'soil health'. Soil quality traditionally possesses a utilitarian orientation, defining the capacity of a specific soil to facilitate a designated use or specific productive output. Conversely, soil health is a ecological concept reflecting the continued capacity of the pedosphere to operate as a vital, living system that sustains plant, animal, and human life (Kundu and Biswas, 2025) Within the FWS framework, we prioritize “soil health” to capture this systemic biological integrity. Furthermore, rather than viewing soil functions (e.g., nitrogen mineralization, water retention) as abstract processes, the thesis considers these functions and the subsequent ecosystem services they generate as the performances' of the soil (Dominati et al., 2016; Séré et al., 2024). A healthy soil performs by delivering multiple ecosystem services simultaneously.

By framing the biological functions of soil, water, and plants as services and disservices, we shift the analytical focus from accounting of material stocks to a

assessment of urban gardens as living, multifunctional infrastructure (Zhang et al., 2019). Traditional nexus frameworks evaluate efficiency through static mass balance, measuring the raw volume of water applied against the final yield of edible biomass. Integrating the ES and EDS framework translates these physical fluxes into ecological outcomes. For instance, the interaction between applied water and an engineered garden soil profile does not merely consume a resource; it drives a performance metric. When highly porous urban soils absorb sudden precipitation, the system delivers a critical regulating ecosystem service by mitigating localized surface flooding. However, if that identical hydrological flux saturates heavily amended compost profiles, it risks leaching excess phosphorus and mobilizing latent trace elements into adjacent municipal infrastructure, actively generating an ecosystem disservice (von Döhren and Haase, 2015). While existing urban nexus literature frequently correlates biological integration with cumulative ecological benefits, this specific framework explicitly codifies disservices (Campagne et al., 2017). This mandates a different evaluation of urban cultivation, recognizing that optimizing for a provisioning service inevitably triggers metabolic and hydrological trade offs within the localized urban ecosystem.

Following this framing, we argue that both ESs and EDSs must be incorporated into the center of the FWS nexus as the implicit functions that mediate the links between its components, rather than as simple outputs. The role of ESs/EDSs in

facilitating synergies and, more critically, in exposing trade-offs becomes explicit when considering the system's underlying biophysical state (Séré et al., 2024). The soil's biophysical structure and microbial processes are the foundation that underpins ecosystem functions. These functions are essential for delivering services valued by urban dwellers, such as fresh food, aesthetic beauty, or microclimate regulation.

The FWS nexus is best understood by characterizing the distinct but interdependent roles of its components. Water serves as the dynamic medium, facilitating primary flow and nutrient transport, which in turn supports plant growth. Food, or more broadly biomass, represents the productive output and the principal objective of management interventions. At the core sits soil, the foundational living infrastructure of the system. Unlike water or food, soil is a capital asset whose function is determined by its state. We can distinguish between its inherent properties (e.g. texture, mineralogy), which define the system's baseline capability, and its dynamic properties (e.g. soil organic carbon, aggregate stability, biota), which reflect its current health and are directly modified by management (Robinson et al., 2009). It is the management interventions targeting food production that alter these dynamic properties, thereby mediating the soil's relationship with water. For example, a decision to apply compost to increase crop yield enhances the dynamic property of soil organic carbon, which in turn improves the soil's capacity to store water,

demonstrating a synergy between the food, water, and soil dimensions. It is these changes in soil-mediated function, driven by the interactions between food, water, and soil, that ultimately manifest as the ecosystem services and disservices valued by society.

3.3.1 Ecosystem services from UFGs

The previous sections have established the foundation of clarifying the FWS nexus and how FWS nexus interactions generate ESs and EDS. In this section, ESs and EDSs in existing research literature are summarized and categorized to provide a clearer look into how ESs and EDSs relate to FWS. The Common International Classification of Ecosystem Services (CICES) was used to categorize common ESs into provisioning, regulating, and maintenance, and cultural groups. Table 3.1 presents the list of perceived ESs streaming from UFGs identified from Italy, Spain, Europe, and Southeast Asia, based on Langemeyer *et al.* (2016), Camps-Calvet *et al.* (2016), Sanyé-Mengual *et al.* (2018), and Lourdes *et al.* (2021). While much can be discussed about the ESs and EDSs' perception, assessment methodology, and applications, this section focuses on using them to clarify how the FWS nexus interacts among its components that shape the flow of ESs and EDSs toward human well-being capital, which is essential for managing the FWS nexus effectively.

Table 3.1. List of common perceived ecosystem services from urban gardens (Source: synthesis from Langemeyer *et al.* (2016), Camps-Calvet *et al.* (2016), Sanyé-Mengual *et al.* (2018), and Lourdes *et al.* (2021))

Provisioning Services	Food (edible parts of vegetative plants)
	Material (fuels, raw materials)
	Medicinal and aromatic plants
Regulating and Maintenance	Air quality and microclimate regulation
	Biological control (pets and pathogens)
	Biodiversity and Habitat Provision
	Carbon storage and sequestration
	Erosion control and soil fertility conservation
	Flood regulation and mitigation (drainage and buffer)
	Water quality and water regulation
	Waste decomposition
	Pollination
Cultural Services	Cultural history, identity, and heritage
	Social cohesion, integration, and community building
	Aesthetics, spirituality, religion, inspiration, recreation
	Sense of place, political realization
	Learning, education, and research
	Physical exercise, stress reduction, and mental health

3.3.1.1 Provisioning Services

The most direct and tangible service provided by UFGs is the production of edible crops. This service is the primary output of the FWS nexus, where soil fertility and structure (S) mediate water availability (W) to support the growth of edible crops (F). Beyond subsistence, this local food production can generate significant economic outcomes, particularly in low socio-economic areas, by supplementing household food budgets and fostering local economic development (Mensah, 2023). This service directly addresses concerns of urban food security and sovereignty by providing communities with greater control over their food, materials, flowers, and medicinal supplies.

3.3.1.2 Regulating and Maintenance Services

A majority of research related to regulating services emerges from the garden's capacity to modulate local environmental conditions (Haase et al., 2014; Langemeyer et al., 2016). While UFGs and other urban green spaces only account for a small fraction of the global biosphere, their contribution to local environmental resilience and human well-being is of significant importance and well-documented (Cabral et al., 2017b; De la Sota et al., 2019; Jha et al., 2023).

A key service is *stormwater management* and *flood mitigation*, a direct outcome of the Soil-Water dynamic. Healthy, uncompacted urban garden soils, rich in organic matter, function like sponges. They exhibit higher hydraulic conductivity and water-holding capacity compared to typical compacted urban soils or

impervious surfaces. This enhanced infiltration reduces surface runoff, mitigating local flooding and decreasing the load on municipal stormwater systems. Conversely, urban soil compaction can reduce infiltration rates by as much as 70% to 99% (Gregory et al., 2006), effectively turning permeable land into a runoff-generating surface.

UFGs also provide microclimate regulation, an ES that arises from Food-Water interconnections. The canopy of garden plants provides shade, which can significantly reduce surface temperatures. Simultaneously, the process of evapotranspiration, fuelled by water drawn from the soil, releases water vapor and reduces the temperature of the surrounding air. This localized cooling helps mitigate the UHI effect. The effectiveness of this cooling is influenced by the density and structural complexity of the plant canopy; multi-layered plantings of trees, shrubs, and groundcover are more effective than single-layer vegetation (Egerer et al., 2019).

Furthermore, UFGs are hubs for waste recycling and nutrient cycling, embodying a circular economy model (Salomon et al., 2020). The practice of composting organic waste, such as food scraps and yard trimmings, and applying it to garden soil is a central FWS interaction. This process diverts waste from landfills and transforms it into a valuable amendment that improves soil structure (S), enhances fertility for food production (F), and increases water retention capacity (W).

UFGs contribute significantly to biodiversity maintenance in otherwise fragmented and ecologically simplified urban landscapes (Jha et al., 2023). By cultivating a diversity of flowering plants and creating structurally complex habitats, these gardens serve as crucial refuges and ecological corridors for urban wildlife, particularly pollinators like bees and butterflies, as well as birds (Speak et al., 2015). The health of the soil ecosystem (S) and the diversity of cultivated plants (F) underpin this service, which in turn supports other services like pollination for food production.

3.3.1.3 Cultural Services

Perhaps the most deeply felt benefits of UFGs are the cultural services they provide. These gardens are strongly associated with improved health and well-being (Rao et al., 2022). They offer opportunities for physical activity and increase access to fresh, nutritious food. Moreover, numerous studies have documented the profound mental health benefits of gardening, including significant reductions in stress, anxiety, and depression, and improvements in mood and overall life satisfaction (Genter et al., 2015).

UFGs are also unique urban green spaces that foster social cohesion and community building (Delshad, 2022). They act as neutral grounds where diverse residents can interact, share labor, solve problems collectively, and build

relationships, thereby strengthening neighborhood trust and social capital. This process of community building enhances the social resilience of neighborhoods.

Finally, UFGs serve as powerful platforms for education and skills development. They are living classrooms where participants of all ages can gain practical knowledge about ecology, food production, and nutrition (Gregory et al., 2016), directly enhancing the "human capital" that is essential for managing the FWS nexus effectively.

3.3.2 Ecosystem disservices from UFGs

The definition of EDS is "*functions of ecosystems that are perceived as negative for human well-being.",* directly opposing the beneficial outputs classified as ecosystem services.(Herd-Hoare and Shackleton, 2020; von Döhren and Haase, 2015).While the ES framework evaluates the dividends of natural capital, the EDS framework quantifies the environmental, economic, and social friction generated by those same biological processes. Many are concerned about the EDS concept's potential to compromise conservation efforts or hamper the advancement of nature planning in cities. However, people inevitably experience nuisances and harm from ecosystems in their daily lives; various forms of EDS are commonly discussed by the media (Schröter et al., 2014). Acknowledging these potential harms is critical for balanced management and governance. Based on the framework established by Vaz et al. (2017) these disservices can be systematically

categorized into three primary domains: human health disservices, ecology and resource disservices, and economic and social disservices.

Within the current literature on urban agriculture, the application of the EDS concept remains disproportionately marginalized. Agronomic and urban planning research exhibits a persistent normative bias, predominantly optimizing and assessing urban food gardens for their positive externalities (Campagne et al., 2017). When the EDS framework is deployed in urban agriculture, it is typically restricted to cataloging localized aesthetic nuisances, pest proliferation, or structural maintenance burdens, rather than evaluating fundamental metabolic trade-offs. Integrating the EDS concept into the Food-Water-Soil nexus corrects this structural bias, developing an evaluation where the metabolic costs of provisioning services are explicitly quantified alongside their benefits.

Table 3.2. List of common urban ecosystem disservices (Vaz et al., 2017)

Human health disservices <*infectious disease; toxicity and allergenicity; other pollution effects*>	Animal and insect bites
	Contaminated food (contamination accumulation)
	Zoonotic diseases and pathogens
	Skin irritation and pollen-induced allergies
	Exposure to soil contamination through inhaling
Ecology and Resource Disservices <*direct and indirect ecological and environmental costs and impacts*>	Water depletion (used for watering)
	Water quality – fertilizer and pesticide runoff
	Soil nutrient inputs – altered nutrient cycles
	Green waste
	Air pollution emissions from decomposition
	Introduction of invasive species

	Maintenance cost (planning, pruning, mulching, irrigation, fertilization)
	Safety hazard from the tree/branches falling
	Species and landscapes perceived as irritating or unpleasant
Economic and Social Disservices *<disrupting physical, personal, financial stabilisation; impacts on mental/cultural interactions with nature; prevention of physical interaction with nature>*	Green gentrification
	Sounds and smells produced by ecosystem functions
	Presence of weeds, pets, mosquitoes
	Habitats associated with the unknown, remoteness, or wilderness are considered unpleasant for outdoor activities
	Fear and risk of wilderness (animals and lack of light in dense vegetative areas)

3.3.2.1 Human Health Disservices

The presence of urban flora and fauna exerts subtle yet significant influences on human health, often operating beneath the threshold of conscious perception. A significant health concern stems from soil and water contamination. Urban soils (S) are frequently contaminated with heavy metals such as lead (Pb), zinc (Zn), and cadmium (Cd) from legacy sources like leaded gasoline, industrial emissions, and lead-based paint (Ashrafzadeh et al., 2018; Jean-Soro et al., 2015; Leitão et al., 2018). Using contaminated stormwater runoff (W) or locating gardens near high-traffic roads can introduce these pollutants into the garden environment. This creates multiple exposure pathways, including direct ingestion of soil (especially by children), inhalation of contaminated dust, and consumption of produce (F) that has absorbed heavy metals, posing serious long-term health risks. A

comprehensive systematic review analyzing 143 urban sites across 29 European countries demonstrates that metal contamination is a widespread, continent-level challenge. Elements such as lead (Pb), zinc (Zn), copper (Cu), chromium (Cr), and nickel (Ni) frequently exceed national safety thresholds within urban environments (Binner et al., 2023).

The risk of pathogen exposure is another health disservice. The use of untreated or inadequately treated greywater (W) for irrigation can introduce a range of pathogens, including E. coli and Salmonella, into the garden (Shqerat and Al-Tabbal, 2025). Similarly, applying improperly managed or "cold" composted animal manure (S) can contaminate soil and produce harmful bacteria, creating a direct risk of foodborne illness.

Gardens can also be a source of pests and allergens. They can provide habitats for pests such as rodents and certain insects, which may become a nuisance to gardeners and adjacent residents. Furthermore, the cultivation of numerous plant species, particularly wind-pollinated varieties, can release pollen that triggers allergic reactions in susceptible individuals, contributing to local air quality concerns for some. Additionally, there are numerous ornamental, crop, and weedy plants that may induce contact dermatitis in certain individuals, e.g. dandelion, ginkgo trees, common ivy; read more in Douglas *et al.* (2020).

3.3.2.2 Ecology and Resource Disservices

A primary ecosystem disservice manifests through the consumption of potable water. The Food-Water nexus dictates a direct metabolic trade-off: optimizing provisioning services frequently necessitates substantial hydrological inputs. Because urban environments restrict access to safe surface water and localized groundwater is often contaminated, urban cultivators predominantly rely on treated municipal water systems (Wortman and Lovell, 2013). This reliance decouples the garden from the natural watershed and forces it into direct resource competition with residential and commercial municipal demand. Consequently, urban agriculture places a measurable strain on potable water supplies, exacerbating resource vulnerability in arid, drought-prone, or rapidly expanding urban regions (Chhour and Carrasquillo, 2025).

Poor management can also lead to nutrient runoff and water pollution (Wielemaker et al., 2019). The over-application of fertilizers or nutrient-rich compost (an F-S interaction) creates environmental risks that are strictly dictated by the physical state of the soil (S) and irrigation practices (W). In well-structured or highly porous soils, excessive irrigation can cause mobile nutrients, such as excess nitrogen and phosphorus, to leach downward into the groundwater. Conversely, in compacted urban soils characterized by poor infiltration capacity, these nutrients cannot easily leach through the profile; instead, they are mobilized by surface water and carried away as lateral runoff, potentially contributing to the eutrophication of adjacent urban waterways.

Finally, UFGs generate green waste. Non-edible plant parts, pruned branches, and end-of-season crop residues constitute a waste stream that requires management. As UFGs and other urban green spaces increase worldwide, leading to a higher generation of green waste (Viretto et al., 2021). If not composted effectively on-site, this green waste can place an additional burden on municipal waste collection and processing systems.

3.3.2.3 Economic and Social Disservices

UFGs are not without costs. Maintenance costs, including the financial outlay for tools, seeds, water, and soil amendments (built capital), as well as the significant investment of time and labour (human capital), can be a substantial barrier to participation, particularly for individuals and families with limited resources.

The shared nature of many community gardens can also lead to social conflicts. Disagreements over plot maintenance standards, water use, the introduction of "weedy" or unkempt plants, and differing aesthetic visions for the space can create tension among gardeners and with the surrounding community, undermining the very social cohesion the garden is meant to foster (Haase and Gaeva, 2023).

Green gentrification exemplifies a nuanced and troubling form of social injustice. Urban greening initiatives provide essential ecosystem services**,** such as aesthetic

appeal, social cohesion, and community resilience**.** Their effectiveness can unintentionally heighten the attractiveness of neighbourhoods to affluent residents and developers (Marche, 2015). This often leads to rising property values and rents, forcing long-standing, low-income populations to displace, despite benefiting from these environmental enhancements (Quinton et al., 2022). Consequently, the development of localized ecological assets can paradoxically intensify social and economic disparities, underscoring a critical drawback of urban greening policies that demands re-evaluation.

3.3.3 EDS and ES feedback loops on FWS

The relationship between ES and EDS is not static; it is part of a dynamic feedback loop that influences management and the state of the FWS nexus over time. As illustrated in Figure 2, the societal experience of a disservice can trigger a response that alters the ecosystem's structure and function, thereby changing the future flow of both services and disservices (refer to Figure 3.2).

For example, a pest outbreak (an EDS) in a allotment garden might initially be met with the application of chemical pesticides. This response, while addressing the immediate nuisance, could generate further disservices, such as contaminating the soil (S), harming beneficial pollinating insects (reducing a supporting service), and posing health risks to gardeners. The negative experience of these secondary disservices may lead to a new societal valuation—a greater appreciation for

ecological pest control. This new value could drive a different response: the adoption of integrated pest management practices, such as planting pollinator-friendly species to attract predatory insects. This action directly alters the garden's ecosystem structure (increasing plant diversity) for the next cycle, aiming to enhance the ES of natural pest regulation while minimizing the EDS associated with chemical use.

This cascade demonstrates that disservices are not merely negative endpoints but are also critical signals within a social-ecological system. They reveal unsustainable practices and create opportunities for learning and adaptation. Recognizing and responding to these signals is fundamental to the adaptive management of the FWS nexus, allowing gardeners and planners to iteratively refine their practices to minimize harms and optimize the net positive contribution of the UFG to urban well-being.

Urban gardens incorporate practices that utilize natural processes to enhance agricultural productivity sustainably, while also promoting soil health, effective water management, and biodiversity conservation within the urban environment. (Brauman et al., 2020; Nassary, 2025). It is at this critical interface of natural assets and human well-being that our FWS framework becomes operational. Urban gardens can be understood as a form of cultivated natural capital, a hybrid system that is neither entirely natural nor purely an artifact of human creation (Hernández-Blanco and Costanza, 2018). Urban gardens, such as allotments or

communal gardens, require minimal energy input for production (Caputo et al., 2023). In contrast, soil is the foundational medium where critical interactions occur, and managing soil health through sustainable agricultural practices is of significant importance for long-term urban resilience (Nassary, 2025); therefore, soil should be placed at the centre of nexus thinking, especially in planning and evaluating the effectiveness of soil-based NbS.

3.4 IMPLICATIONS FOR NEXUS GOVERNANCE AND ADAPTIVE MANAGEMENT

Urban gardens are often considered a type of NbS (Cabral et al., 2017a; van der Jagt et al., 2017). Adopting a dual ES and EDS perspective is fundamental to navigating the complexities of the FWS nexus and achieving sustainable outcomes in urban gardens. Rather than simply maximizing benefits, this balanced lens aims to optimize the net contribution of these systems to urban well-being.

First, this approach offers a far more comprehensive and accurate understanding of the garden's internal dynamics. The goal of FWS nexus thinking is to develop integrated management practices that recognize the profound interdependence of food production, water use, and soil health. The soil, in particular, acts as a living ledger; its health is a direct reflection of past management choices and a predictor of future potential. Spatially and temporally mapping the flows of both services (e.g. food provision, stormwater infiltration) and disservices (e.g. potable water

consumption, nutrient runoff) allows us to identify critical interdependencies and time-lag effects. For example, the decision to maximize yield in one season through intensive irrigation and fertilization can create a “yield drag” in subsequent years by degrading soil structure and depleting organic matter, thus reducing its water-holding capacity (Hatfield et al., 2017). The FWS lens makes this causality visible, transforming our management from a series of isolated actions into a conscious dialogue with the garden’s ecological memory (Cortinovis et al., 2021).

Second, the ES/EDS perspective fosters a more rational and inclusive dialogue among stakeholders. All too often, urban greening initiatives are promoted with a uniformly positive narrative that can obscure real-world conflicts and trade-offs. The FWS framework provides a common, transparent language that makes not only the benefits but also the potential risks and nuisances of urban gardens visible and debatable. This moves the conversation beyond green aesthetics, enabling gardeners, residents, and city planners to openly address conflicts over issues like water rights, pest management strategies, the risk of allergens, or even gentrification pressures associated with new green spaces (Lyytimäki, 2015). By quantifying and qualifying both sides of the ledger, we encourage evidence-based negotiation and the co-design of solutions that reflect the shared goal of minimizing harms while securing benefits. This process enhances the legitimacy of

urban greening policies and fosters a more resilient social fabric surrounding them (Webb et al., 2018).

Furthermore, this dual perspective is a powerful antidote to the fragmented, siloed governance that plagues most municipalities. Acknowledging that urban gardens co-produce a wide array of services and disservices reveals their deep entanglement with multiple domains of urban policy (Haase et al., 2014). The FWS framework allows different city departments to understand the interconnected impact of a single garden, e.g. *public health* (nutrition vs. allergens), *urban hydrology* (infiltration vs. contaminated runoff), *waste management* (composting vs. green waste & odor), and *planning and development* (community building & aesthetic improvement vs land-use conflicts).

Finally, this approach is crucial for moving beyond a mindset of resource extraction and toward a culture of ecological stewardship. It reorients our goal from simply "*producing food*" to "*maintaining the health and functionality of the garden as a long-term urban asset*." Assessing the outcomes of different management practices on the net provision of ESs over EDSs provides a direct feedback loop for continuous learning and improvement. By making the costs of disservices clear, it justifies investments in knowledge, skills, and infrastructure (i.e. human and built capital). This perspective helps us value the garden not just for the harvest it provides, but for its ongoing capacity to function (van der Jagt et al., 2017). It aligns with the "One Health" concept, recognizing that the health of soil, plants, and

people is deeply interwoven and indivisible. Ultimately, governing urban gardens through an FWS-ES/EDS lens is an act of foresight—a commitment to managing these vital urban spaces not for a single season's yield, but for their enduring contribution to a resilient and liveable city for generations to come.

3.5 MANAGEMENT HIERARCHY TO THE FWS NEXUS IN UFGS

Governing urban gardens through an FWS-ES/EDS lens requires moving beyond a simple goal of maximizing benefits and toward a more nuanced approach of optimizing the net contribution of these systems to urban well-being. This necessitates a structured framework for decision-making that is both comprehensive and adaptive. The management hierarchy proposed by Vaz *et al.* (2017), which refines the traditional precautionary principle, offers such a framework. It provides a systematic, step-by-step process for managing complex social-ecological systems by integrating the identification, prevention, and mitigation of harms alongside the protection and restoration of benefits. This hierarchy consists of five sequential but interconnected steps: (1) Identification and Evaluation, (2) Protection and Avoidance, (3) Minimization, (4) Restoration, and (5) Compensation and Adaptation. Figure 3 illustrates the main components and principles of the management hierarchy for ESs and EDSs, modified for UFGs

and FWS nexus. Applying this hierarchy provides an actionable pathway for the adaptive management of the FWS nexus in urban gardens.

Each step of the hierarchy addresses a different aspect of managing the services and disservices that arise from FWS interactions. While visually represented as a prioritized vertical hierarchy to emphasize the precautionary principle, the operational application of this framework is not a linear, one-time process. Instead, the 'Evaluation' in Step 1 and the 'Adaptation' in Step 5 create a crucial, continuous feedback loop that drives adaptive management process.

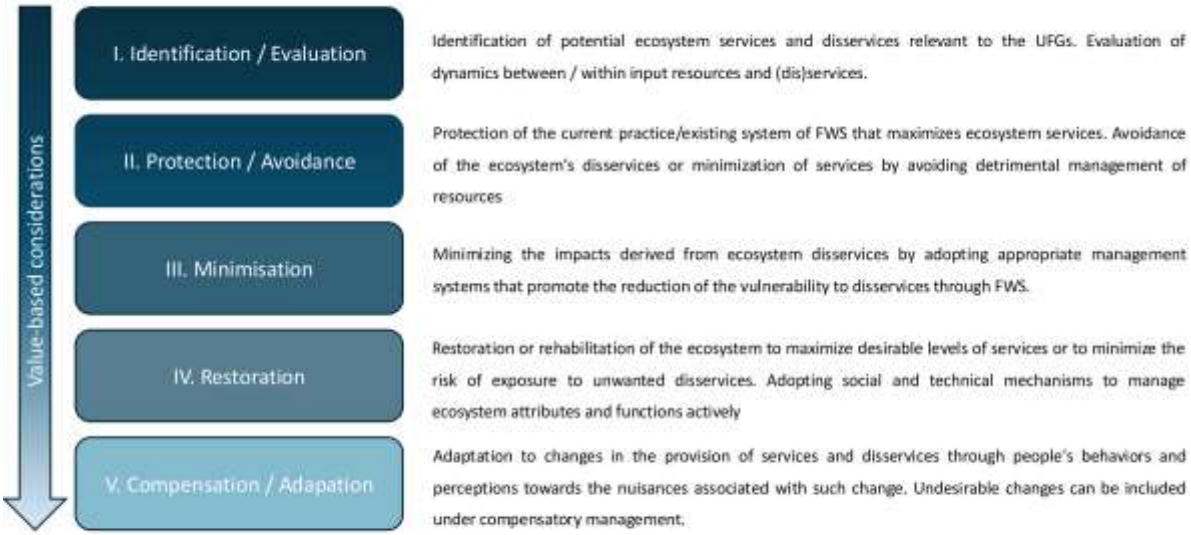

Figure 3.3. Management hierarchy for strategic management of ecosystem services and disservices, adapted from Vaz et al. (2017).

After a management adaptation is implemented (e.g., changing crop types), the system must be re-evaluated to assess its new performance and identify any new

or altered ES and EDS that may have emerged. This iterative cycle of planning, acting, monitoring, and learning is the essence of managing a complex social-ecological system like an urban garden for long-term resilience and net positive impact. Furthermore, this governance framework makes it clear that managing the FWS nexus cannot be a purely technical or ecological endeavour confined within the garden's boundaries. The identification of large-scale social disservices like green gentrification demands that nexus governance extends to the municipal policy level. Minimizing such disservices requires planners and advocates to employ tools beyond the scope of garden management, such as inclusionary zoning, community land trusts, rent stabilization policies, and other anti-displacement strategies. Therefore, a holistic application of the Vaz *et al.* (2017) framework compels a broader interpretation of "social-ecological management" that fully integrates on-site biophysical practices with engagement in urban planning and housing policy.

The following Table 3.3 provides a practical summary of how this management hierarchy can be operationalized to address common challenges within the FWS nexus of urban gardens. It is important to specify that these core challenges, namely Soil Contamination, Water Scarcity, Pest Outbreaks, Social Conflict, and Green Gentrification, originate directly from the primary EDS identified and categorized in Section 3.3.2. The management strategies proposed across the five hierarchical steps are derived from and justified by established literature in urban

agroecology, hydrology, and environmental justice. The information contains in the table were synthesized from various sources: Deeb et al.(2020) and Paltseva et al. (2020) for soil management; Egerer et al. (2018) a Pollard et al. (2018) for water management; Bazzocchi, (2020) for pest management; Fox-Kämper et al. (2018) for social conflict solutions; and (Oscilowicz et al., 2022) for urban green gentrification.

Table 3.3. Application of the Management Hierarchy to FWS Nexus Challenges in Urban Gardens

FWS Challenge	1. Identification/Evaluation	2. Protection/Avoidance	3. Minimization	4. Restoration	5. Compensation/Adaptation
Soil Contamination	Conduct soil tests for heavy metals; research the site's land-use history.	Avoid siting gardens on former industrial land or near high-traffic roads.	Use mulch to reduce dust/splash; wash produce thoroughly; practice good personal hygiene (gloves, handwashing).	Build raised beds with clean, imported soil; amend existing soil with compost/biochar to immobilize Pb.	Grow non-edible plants (ornamentals); implement public health advisories and educational programs.
Water Scarcity	Assess local climate data, water sources, and costs.	Select drought-tolerant crop species and varieties.	Use efficient drip irrigation systems; apply a thick layer of mulch to reduce evaporation.	Amend soil with compost to significantly increase its water-holding capacity.	Install rainwater harvesting systems (e.g. rain barrels); adapt planting schedules to align with rainy seasons.
Pest Outbreaks	Monitor crops for pests and identify beneficial insects.	Plant pest-resistant varieties; create diverse	Use Integrated Pest Management techniques: companion planting,	Actively introduce beneficial insects (e.g. ladybugs) if natural	Adapt crop selection to species that are less

FWS Challenge	1. Identification/Evaluation	2. Protection/Avoidance	3. Minimization	4. Restoration	5. Compensation/Adaptation
		habitats to support natural predators.	mechanical removal (hand-picking), and biological controls.	populations are insufficient.	susceptible to prevalent local pests.
Social Conflict	Facilitate community meetings to identify shared values, goals, and potential points of conflict.	Establish clear, written garden rules, bylaws, and a transparent governance structure from the project's outset.	Implement formal and informal conflict mediation processes; create shared communication channels (e.g. message boards, group chats).	Host community-building events (e.g. potlucks, workshops) to restore social cohesion and trust.	Periodically review and adapt garden rules and governance structures based on community feedback and evolving needs.
Green Gentrification	Analyse local housing market data (rents, property values); engage with residents about displacement concerns.	Prioritize gardens in neighbourhoods with high rates of homeownership or	Advocate for and implement anti-displacement policies (rent control, inclusionary zoning) alongside greening projects.	Establish Community Land Trusts to secure land for permanent affordability and community control.	Develop "right to return" policies for displaced residents; ensure new jobs created by greening prioritize local hiring.

FWS Challenge	1. Identification/Evaluation	2. Protection/Avoidance	3. Minimization	4. Restoration	5. Compensation/Adaptation
		existing affordable housing protections.			

3.5.1 Step 1: Identification and Evaluation

This initial diagnostic phase is the cornerstone of adaptive management. It involves a comprehensive assessment to identify the potential ES and EDS relevant to a specific garden context. This is not a purely technical exercise; it requires participatory engagement with all relevant stakeholders to understand their diverse values, needs, and perceptions of risk. (e.g. gardeners, adjacent residents, community leaders, and municipal officials). Key activities in this stage include:

- *Site History and Context Analysis*: Researching the past land use of the site to identify potential legacy issues, such as industrial contamination.

- *Biophysical Assessment*: Conducting soil tests to determine baseline fertility, structure, and, crucially, the presence of contaminants like heavy metals (S). Water sources (W) must also be evaluated for quality, whether they are municipal tap water, harvested rainwater, or potentially contaminated stormwater or greywater.

- *Trade-Off Analysis*: Making the inherent trade-offs within the FWS nexus explicit. For example, evaluating how plans to maximize food production (F) would impact water demand (W) and the potential for nutrient leaching (S). This step ensures that a full accounting informs decisions of both positive and negative potential outcomes.

3.5.2 Step 2: Protection and Avoidance

This proactive step prioritizes preventing negative impacts before they occur and preserving existing ecological assets. It is the most effective and often the least costly stage of management.

- *Protection*: This involves safeguarding valuable existing resources. For instance, if a proposed garden site contains a patch of high-quality, undisturbed topsoil or hosts a remnant population of native pollinators, management plans should prioritize their conservation.

- *Avoidance*: This entails making strategic choices to prevent the introduction of risks. Examples include siting gardens away from high-traffic corridors to avoid the atmospheric deposition of vehicle-related pollutants, prohibiting the use of materials known to be sources of contamination (such as chromated copper arsenate-treated wood for raised beds), and selecting drought-tolerant crops in water-scarce climates to avoid exacerbating water stress.

3.5.3 Step 3: Minimization

When a disservice cannot be completely avoided, the goal shifts to minimizing its magnitude and impact. This step focuses on implementing best management practices to reduce ongoing harms.

- *Minimizing Water Consumption*: To address the disservice of high potable water use, gardens can implement water-wise strategies. These include the use of efficient drip irrigation systems and the application of mulch to the soil surface to reduce evaporative losses dramatically.

- *Minimizing Pest-Related Disservices*: To reduce reliance on chemical pesticides (which cause disservices of soil/water contamination and harm to non-target species), gardens can adopt Integrated Pest Management (IPM). IPM strategies include companion planting to repel pests, creating insectary plantings to attract beneficial predatory insects, and using mechanical controls like hand-picking pests or using traps.

3.5.4 Step 4: Restoration

This step involves active intervention to repair degraded components of the FWS nexus and rebuild the system's capacity to provide ecosystem services.

- *Restoring Soil Health*: Urban soils are often severely compacted and may be contaminated, making active restoration a critical management action. For sites with heavy contamination or intractable compaction, this frequently involves constructing raised beds to physically bypass the polluted matrix. However, importing established topsoil from rural environments to fill these beds is inherently unsustainable; it degrades soil

resources in one location to improve another and carries significant environmental risks, including substantial carbon dioxide emissions associated with transport. Consequently, sustainable restoration must shift toward the use of constructed soils, or 'Technosols', engineered by valorizing uncontaminated urban waste streams and by-products. By utilizing locally sourced organic and mineral wastes to build the cultivation matrix, this approach adheres to circular economy principles, effectively mitigating urban contamination risks without driving the extraction of finite, non-renewable natural soil resources elsewhere. For less degraded soils, restoration can be achieved by amending the existing soil with large quantities of compost. This practice directly counteracts compaction, rebuilds soil structure, increases soil organic matter, dramatically improves water-holding capacity (W), and can help immobilize certain heavy metal contaminants, reducing their bioavailability.

3.5.5 Step 5: Compensation and Adaptation

This is the final level of the hierarchy, addressing unavoidable negative impacts that persist after all other steps have been taken.

- *Compensation*: This is less common at the scale of a single garden but is relevant in a city-wide planning context. For instance, if a community garden is unavoidably lost to development, a compensatory policy might

require the developer to fund the establishment of a new, equivalent garden space elsewhere in the neighbourhood.

- *Adaptation*: This involves changing human behaviours, expectations, and social structures to cope with unavoidable disservices. A primary example is adapting to water scarcity by shifting crop selection (F) away from water-intensive vegetables like lettuce and toward drought-tolerant alternatives such as pole beans, Swiss chard, or amaranth. Adaptation also includes social strategies, such as developing clear governance structures and conflict resolution protocols to manage social disagreements or implementing public health education campaigns to ensure gardeners follow safe practices (e.g. hand washing, produce washing) to adapt to the risks of soil contaminants.

3.6 CONCLUSION

3.6.1 Nexus Thinking for the Urban Garden

This chapter systematically develops the FWS nexus as a novel conceptual framework, arguing that conventional paradigms, particularly the WEF nexus, are conceptually inadequate for analysing soil-based UFGs. The FWS nexus is presented not as a minor modification but as a necessary paradigm shift, formulated in direct response to the research gaps identified in the preceding

systematic review. That review demonstrated that the WEF nexus, originally conceived to address resource security challenges at large geopolitical scales, is often not a suitable analytical fit for the hyper-local, decentralized, and socially-mediated resource management characteristic of UFGs (Mguni and van Vliet, 2020). Applying such a technocratic, resource-focused framework to a neighbourhood garden risks overlooking the non-material benefits, such as social cohesion, education, and cultural heritage. The FWS nexus repositions soil from a passive substrate to the foundational living infrastructure and capital asset whose health mediates the system's core functions. This re-centring aligns with a growing body of scholarship advocating for a "soil-centric" approach to urban resilience (Pramanick et al., 2021), which recognizes soil as critical infrastructure on par with engineered systems. It also answers broader calls within sustainability science to place soil at the very heart of nexus thinking (Lal et al., 2017).

The development of the FWS nexus, therefore, represents more than a simple technical adjustment; it is a response to a fundamental epistemological mismatch. The WEF nexus, born from a macro-scale, engineering, and resource-security perspective, carries an inherent epistemology that prioritizes quantifiable, fungible resource flows. In contrast, UFGs are complex socio-ecological systems often dominated by qualitative, incommensurable social and cultural values and governed by informal, community-level processes. The FWS nexus, by centring the living soil and employing ES and EDS as its primary analytical lens, is a deliberate

effort to construct a framework whose epistemology aligns with the socio-ecological reality of its subject, thereby offering a useful mode of analysis.

3.6.2 FWS Nexus for Socio-Ecological Management

Beyond its utility as a descriptive tool, the FWS framework offers a prescriptive model for governance. The framework's constituent parts, namely the ES/EDS lens and the management hierarchy, are not disparate elements but form an integrated system for the adaptive management of UFGs as complex adaptive systems. From this perspective, a UFG is a classic Socio-Ecological System (Liu et al., 2023), where social components (gardeners, community norms, governance structures) and ecological components (soil, water, plants, biota) are inextricably linked through a web of dynamic feedback loops. The resilience of such a system is defined by its capacity to absorb disturbances while maintaining its core functions, a capacity that depends on continuous learning and adaptation.

The management hierarchy proposed in this chapter practically applies the theoretical adaptive management cycle by reframing EDS not merely as negative outcomes to be minimized, but as vital feedback signals that reveal system vulnerabilities and trigger learning (Olsson et al., 2004). This reframing establishes a crucial feedback loop between assessment and governance, transforming management from a static set of rules into a dynamic dialogue with the garden's evolving ecological reality (Garmestani et al., 2023). Ultimately, the FWS framework compels a direct confrontation with EDS; by actively recognizing and adapting to these disservices rather than suppressing them, a system increases its

adaptive capacity and builds long-term resilience through a structured process of learning from failure.

3.6.3 Future directions or UFGs resilience

This chapter's development of the FWS nexus provides a foundation for a more integrated and transdisciplinary science of urban agriculture. Looking forward, the future path lies in fostering research that intentionally bridges the methodological divides identified in the preceding review. This includes using the empirical, ground-truthed soil health data generated by field-based studies to parameterize and validate more sophisticated systems models of the FWS nexus. It also requires integrating the participatory methods of socio-ecological assessment into spatial planning processes to ensure that the criteria for optimizing garden placement are co-created with communities, thereby mitigating the risk of top-down, unjust outcomes

CHAPTER 3 SUMMARY

- **Methodology**: Theoretical formulation combining the ES/EDS cascade model with an adaptation of the participatory MESMIS Framework
- **Key Results**: Developed the FWS nexus framework, successfully repositioning soil from a static substrate to a central capital asset. Established a 5-step Management Hierachy for navigating socio-ecological trade-offs

4 ECOSYSTEM SERVICES AND DISSERVICES PERCEIVED BY NANTES URBAN GARDENERS

DISCLAIMER

This chapter is a novel contribution to the dissertation. It will be submitted to the *Ecosystem and People* journal or *Ecosystem Service* journal, under the title "*Perceived ecosystem service and disservice synergies, trade-offs and bundles in urban gardens of Nantes, France.*". The paper is authored by:

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Data and code availability

The dataset and all R scripts used for the statistical analyses presented in this chapter have been permanently archived. The materials are publicly available on GitHub and can be accessed at: https://doi.org/10.5281/zenodo.17379253.

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Abstract

This chapter analysed the perceived benefits and drawbacks of 54 urban gardeners in Nantes Nord, a district targeted for urban regeneration, to inform sustainable governance. Using a multi-phase statistical analysis of survey data on perceived ecosystem services (ES) and disservices (EDS), the research reveals that gardener perceptions are organized into four fundamental bundles: (1) Nuisance, (2) Ecological Stewardship, (3) Pollution, and (4) Well-being. The analysis demonstrates that these perceptions are shaped more profoundly by social identity (person) than by physical location (place), with significant gendered differences in valuing care-related services and perceiving risks. The findings align with the necessity of integrating user perceptions and preferences in developing and maintaining NbS in urban planning, showing how a granular understanding of ES/EDS synergies and trade-offs can lead to more effective, equitable, and resilient management of urban gardens.

Keywords: *urban garden, ecosystem services, ecosystem disservices, trade-offs, synergies.*

4.1 INTRODUCTION

The 21st century is unequivocally the urban century. With a majority of the global population now residing in cities (United Nations, 2019), the pursuit of sustainable urban development has become a paramount global challenge. In response, urban planners, policymakers, and researchers are increasingly turning to Nature-Based Solutions (NbS) as a strategic framework for enhancing urban resilience, conserving biodiversity, and improving human well-being (Frantzeskaki, 2019; Lafortezza et al., 2018; Nesshöver et al., 2017). Urban nature delivers multiple ecosystem services (ES) necessary for human health and well-being (Daily et al., 1997; Millennium Ecosystem Assessment, 2005). These solutions, which leverage the functions of natural ecosystems, represent a shift away from purely engineering-based approaches towards more integrated, adaptive, and multifunctional urban interventions. Inevitably, natural ecosystem also generates ecosystem disservices (EDS) (Lyytimäki and Sipilä, 2009; Pereira et al., 2023; von Döhren and Haase, 2015).

While ES or nature's contribution to people has been extensively studied (IPBES, 2019), EDS are often less considered and less discussed, yet equally important for urban ecosystem management (Lyytimäki et al., 2008; Schaubroeck, 2017). Previous work has shown that EDS can have a profound impact on economic loss and people's well-being in home gardens if not appropriately managed (Herd-Hoare and Shackleton, 2020). Risks from soils contaminated with heavy metals

from geogenic origins (Jean-Soro et al., 2015) or industrial inheritance (Howard et al., 2013) are frequently discussed without necessarily being categorized as EDS.

In the previous chapter, we established the theoretical construction of the ES and RDS model in the resource management framework (FWS). To understand how the EDS and EDS play their roles in the dynamic feedback loop that influences management and the state of urban garden resources over time, this chapter investigates the perceptions, values, beliefs, and concerns of the people who interact with these spaces daily. Understanding their relationships, synergies, and trade-offs can determine levels of engagement, stewardship, and community ownership in urban gardens.

The primary objective of this chapter is to systematically deconstruct and model the perceptual framework of urban gardeners in Nantes Nord. To achieve this, the analysis proceeds through a multi-phase, sequential methodology. We begin by establishing a detailed demographic and behavioural profile of the gardeners, followed by quantifying their perceptions of the benefits (Ecosystem Services – ES) and drawbacks (Ecosystem Disservices – EDS) associated with their gardens, exploring the degree of consensus and disagreement within the community. Subsequently, it investigates the potential drivers of these perceptions, comparing views across different garden sites and between genders. Finally, we map the inter-relationships between individual perceptions to synthesize them into a coherent, underlying model of the gardeners' viewpoint.

Before properly placing the gardeners' views in Nantes Nord into context, it is important to differentiate between the social perceptions of individual and collective urban gardening, as outlined in key academic reviews. Traditional individual gardening, represented by allotments, has historic roots in working-class subsistence but is now often seen in modern literature as a space for personal autonomy, leisure, and secure food production. Notable studies highlight that allotments are closely linked to personal identity, cultural heritage, and physical well-being through direct, sensory interaction with the plot (Maćkiewicz et al., 2021; Sapin et al., 2023). In contrast, collective or community gardens are defined by shared spatial management and communal goals rather than individual ownership. Foundational reviews of community gardens show they are mainly viewed as social infrastructure, driven by aims to improve community cohesion, environmental learning, and social empowerment (Scheromm, 2015). Recent comparative studies note that whileens promote social inclusion and environmental education among marginalized groups (Maćkiewicz and Asuero, 2021), allotments tend to support greater productivity and independence because of more secure tenure. Although both serve as urban NbS, their social images differ dramatically: allotments focus on personal responsibility and food security (Crouch, 2003), while collective gardens are seen as spaces for civic participation, social negotiation, and reconnecting with agriculture (Guitart et al., 2012). Recognizing this difference is vital, as overlapping these perceptions influences the various values, motivations, and concerns of urban gardeners.

4.2 METHODOLOGY

4.2.1 Study area

The city of Nantes serves as the administrative capital of the Pays de la Loire region in France. Covering an area of 65.19 km², it ranks as the sixth largest city in France by population, with 325,070 inhabitants recorded in 2022 (Insee, 2025a). Nantes is also the principal municipality within Nantes Métropole. Historically, the city has been renowned for its horticultural and botanical activities, a tradition that has been strengthened through robust political support and active public engagement. The city features an extensive network of rivers, parks, and green corridors, specifically along the Loire, Erdre, Cens, Gesvres, Chézine, and Sèvre rivers, which enhance its biodiversity and facilitate pedestrian movement. Notably, approximately 60% of Nantes's land comprises natural and agricultural areas. Among these green spaces are 27 family gardens dispersed throughout the city (Nantes Nature et Jardins, n.d.), totalling 1,163 garden parcels ranging from 50 to 150 m² each. These gardens are managed collectively by volunteer organizations of gardeners, which maintain a formal connection with the Nantes municipal government via the Department of Nature and Gardens.

This study focuses on Nantes Nord, a district situated in the northern part of the Nantes municipality, covering approximately 7.6 km² (760 hectares). Although often regarded as Nantes's greenest district, with 62 m² of green space per

inhabitant, it also exhibits the highest density of social housing, with 37% of residents living in such accommodations. This combination presents complex socio-economic, security, and health challenges (Bodénan and Béchet, 2023). In response, Nantes Métropole has initiated the "Projet Global Nantes Nord" to enhance living conditions, promote social cohesion, and support economic development in the area. The project is financed by the ANRU (Agence Nationale pour la Rénovation Urbaine) with a duration of 15,5 years until 2035. As part of this initiative, the city partnered with the URBiNAT project in 2016 to explore and implement urban nature-based solutions (NbS), fostering cross-sector collaboration aimed at addressing urban complexities. Allotment gardens serve as a prominent example of these NbS. Currently, the district features five collective gardens with a total of 210 plots (Nantes Métropole, 2025). Our research reached all five of these gardens: Angle Chaillou (AC), Amande (AM), Bruyères (BR), Eglantiers (EG), and Cressonière (CR).

First, background information related to previous and ongoing projects focusing on urban gardens in the study area was collected, alongside regulations and policy documents about urban gardening in Nantes. Details of the study context are introduced in depth in Chapter 5, Section 3.1; in this chapter, only information relevant to the analysis is provided. Perceptions were measured on a 4-point ordinal Likert scale, ranging from "Not important/concerned" (1) to "Highly important/concerned" (4). Data were collected through a structured

survey that recorded demographic information, gardening behaviours (e.g., visit frequency and duration), and perceptions of 10 specific ES and 11 EDS. The origins of these selected ES and EDS typologies were systematically synthesized from established frameworks within urban ecology and agroecology literature; for instance, the ES classifications build upon works such as Camps-Calvet et al. (2016); Langemeyer et al. (2016), while the EDS categorizations utilize typologies from (Vaz et al. (2017) and von Döhren and Haase, (2015). The complete list of these 21 items (spanning services such as Food Provision and Water Regulation, to disservices like Soil Pollution and Water Consumption) alongside their academic origins and qualitative proxies, is explicitly organized and presented in Table 4.1. To maintain the narrative flow and analytical focus of the chapter, the exact phrasing of the questionnaire items utilized to evaluate each of these factors is provided in the comprehensive survey grid in Appendix 4. During the interview process, we focused on those concepts most relevant to gardeners, intentionally combining overlapping services, such as aesthetic appreciation and mood enhancement, into broader categories like 'Mental Health' to reduce respondent fatigue and conceptual confusion. It contains a total of 43 questions that are divided into two major components, one focusing on the perceptions of gardeners and the other on the extensive use of resources and garden practices for the sustainability analysis of Chapter 5. Interviews were conducted in French and audio-recorded with participant consent.

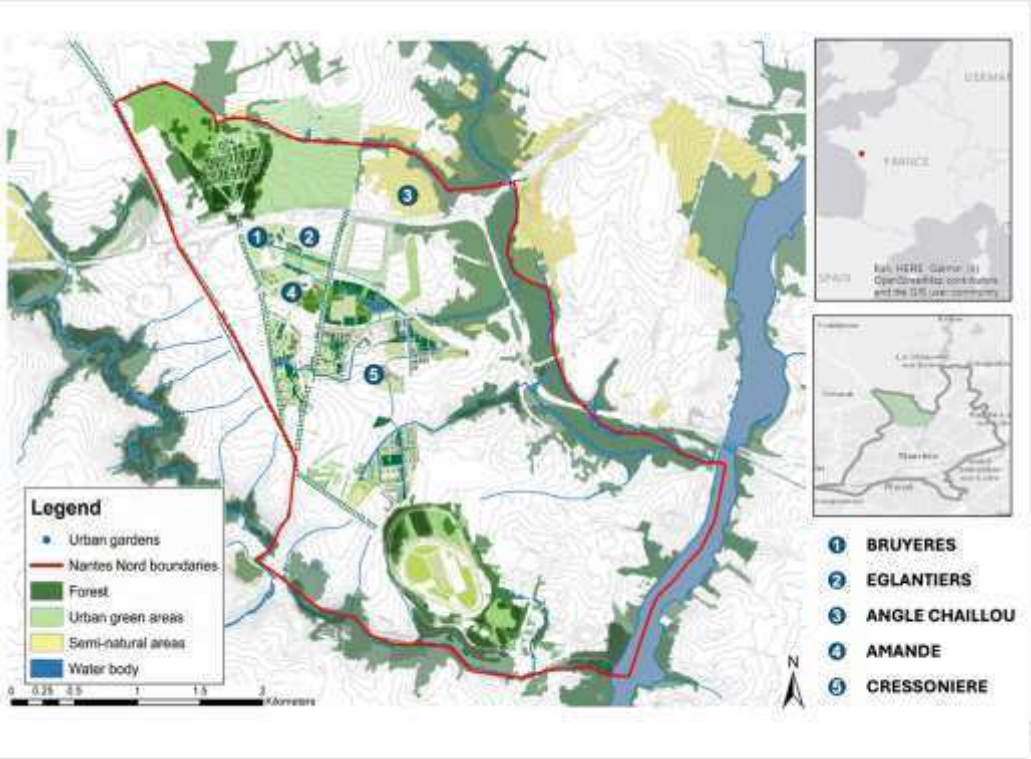

Figure 4.1. Location of studied gardens. Data from Nantes Metropole and Projet global

Additionally, during the interview process, we excluded ES and EDS, for which several gardeners expressed their lack of sufficient understanding to rate accurately, such as the global climate regulation service. Table 4.1 summarizes the final list of ES and EDS in this study.

Table 4.1. Typologies of ecosystem services and disservices in this study

Services and Disservice from urban garden	Qualitative proxies	References
Ecosystem service		
Air Quality	*Air filtering pollution and particulates from vegetation*	Camps-Calvet et al., 2016; Evans et al., 2022; Langemeyer et al., 2016
Biodiversity	*Richness and diversity of plants and animals that contribute to healthy urban garden systems*	
Education	*Knowledge acquired about the structure and functioning of the current and past natural environment*	
Food Provision	*Vegetative parts that are harvested and used for human consumption*	
Medicinal & Aromatic	*Flowers, herbs, and other parts of plants are used for cooking and medicinal purposes.*	
Mental Health	*Mood improvement and stress reduction associated with working and leisure time spent in gardens*	
Physical Health	*Gardening as part of the physical exercise, improving bodily functions*	
Social Cohesion	*Increments in social interactions and relations through time spent in gardens*	
Soil Conservation	*Protecting soil from water and wind erosion*	
Water Regulation	*Water storage, purification, and groundwater recharge from soil and vegetation*	
Ecosystem disservices		
Air Pollution	*Pollution linked to volatile compounds emitted by plants*	Vaz et al., 2017; von Döhren and Haase, 2015
Allergies	*Pollen release that provokes allergic reactions or intoxications*	
Pet/Insect Bites	*Animal or insect bites on humans*	
Food Contamination	*Risk of contaminated vegetables, herbs, and fruits being consumed by humans*	
Maintenance Cost	*Costs associated with installing and maintaining gardens (seeds, equipment, materials, rent)*	
Fear of Wilderness	*Fear and risks of wilderness due to lack of light or attack by animals*	

Services and Disservice from urban garden	Qualitative proxies	References
Unpleasant Odor	*Smells produced by animals, plants, or decomposing matter, such as green waste*	
Water Consumption	*Amount of water used for plant growth*	
Soil Pollution	*Contaminated soil that can affect human health (inhalation or swallowing), or vegetation quality*	
Water Pollution	*Contaminated water that can affect human health (inhalation or swallowing) or vegetation quality*	
Green Waste	*Organic waste from plants (leaf litter, roots, branches, etc.)*	

4.2.2 Semi-structured interview

Between April and July 2025, we conducted interviews using non-participant and participant observation techniques (Bessette, 2004). During this period, we engaged with gardeners in their gardens through tasks such as wall painting and weed clearing, where possible. This technique is a bottom-up approach that facilitates communication strategies between researchers and the local communities, where all actors are involved in common tasks that allow strengthening the dialogue and exchange of ideas between them. We interviewed participants from five allotment gardens in Nantes Nord, with each session lasting 45 to 90 minutes, either at community rooms or in their gardens. Initially, interviews focused on garden association board members. We expanded our sample through a snowball approach, asking these members to refer additional gardeners. The study concluded with a total of 54 gardeners (Table 4.2). Additionally, we held four additional meetings with Nantes' urban planning practitioners. Two of them were conducted with Nantes Nature et Jardins Department and the Deputy Mayor of Nantes responsible for Nature in the City and the Agenda 2030. The other two interviews were conducted with non-profit organizations, MAAD (*Maison des Agricultures et de l'Alimentation Durables*) and ECOS. Given the small sample size and the distinct administrative roles of these participants, these interviews were not incorporated into the quantitative statistical modelling. Instead, a highly flexible, semi-structured interview guide was employed. Informants were asked to complete a similar ES and EDS ranking

exercise to establish a comparative baseline of institutional priorities, which was then followed by open-ended, spontaneous discussions regarding their professional mandates, municipal green space policies, and strategic urban development goals. Methodologically, the information gathered from these interviews was subjected to qualitative triangulation. Rather than formal coding, these institutional perspectives were synthesized and utilized specifically within the discussion (Section 4.4) to support empirical claims and to critically contrast the 'bottom-up' grassroots perceptions of the gardeners with the governance frameworks driving Nantes' urban renewal.

Table 4.2. Breakdown of conducted surveys

Garden	N of interview	Total plot	Surface area (m^2)
AC	10	58	14469,12
AM	8	21	4754,45
BR	11	30	11306,78
CR	7	9	1176,76
EG	23	92	23222,69

4.2.3 Statistical analysis

First, descriptive statistics (frequencies, means, medians) were employed to understand the demographic and behavioural profile of the gardeners. Due to the nature of the primary data, which was collected using Likert scales, a series of non-parametric tests were used to analyze the perception of gardeners. Likert-scale data is fundamentally ordinal; it possesses a natural order (e.g. "Highly important"

is greater than "Moderately important"), but the intervals between the categories cannot be assumed to be equal (South et al., 2022). Treating such data with parametric tests (e.g. t-tests, ANOVA), which assume interval-level data and a normal distribution, can lead to statistically invalid and misleading conclusions. Non-parametric methods circumvent this issue by analysing the ranks of the data rather than the raw scores, providing a more robust and appropriate framework for ordinal variables.

Second, given the ordinal nature of the primary outcome variables and the demographic data, the statistical analyses in the initial phases rely on non-parametric methods. These tests, including the Mann-Whitney U test, Spearman's rank correlation, and the Kruskal-Wallis H test, analyse the ranks of the data rather than assuming a specific distribution, making them more robust and appropriate for this type of data. It has previously been employed in a similar manner to analyse the perception of rural residents toward ES of farming landscape (Plieninger et al., 2019). In this study, the Mann-Whitney U test was used to compare time commitment between the two gender groups and the differences in their perception toward EDS and ES, Spearman's rank correlation to assess the monotonic relationship between age group and time commitment, and Kruskal-Wallis H to evaluate the perception across different gardens.

Third, polychoric correlation matrices were calculated to show the synergies and trade-offs between ES and EDS

Finally, Exploratory Factor Analysis (EFA) to discover the latent structure of these services and disservices.

Analysis was conducted using R (R Core Team, 2025), the *tidyverse* package (Wickham et al., 2019), and the *psych* package (Bernaards and Jennrich, 2005). The analysis is affected by the small size of our samples, which is being discussed in depth in Section 4.4.3

4.2.3.1 Comparative analysis

The Mann-Whitney U is the non-parametric equivalent of the independent samples t-test. It is the appropriate method for comparing the distributions of an ordinal dependent variable between two independent groups (McKnight and Najab, 2010). In this study, it was used to compare perceptions between genders (F/M). The test combines all observations from both groups and ranks these combined observations from lowest to highest. The test statistic, U, is calculated based on these rank sums. It essentially tests the null hypothesis that the probability of an observation from one group being higher than an observation from the other group is 0.5. A p-value falling below the established significance threshold ($p > 0.05$) indicates that this null hypothesis is unlikely, leading to the conclusion that the distributions between the two groups are statistically different.

The Kruskal-Wallis H test, the non-parametric equivalent of a one-way ANOVA, was used to determine if perceptions differed significantly across the five allotment garden sites. The test assesses the null hypothesis that the medians of the groups are equal by pooling all data, ranking it, and comparing the mean rank of each group to the overall mean rank (Kruskal and Wallis, 1952) by the test statistic H.

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1)$$

When N is the total sample size, k is the number of groups, R_i is the rank sum for the group i, and $n_i$is the sample size of group i. A statistically significant result ($p < 0.05$) indicates that at least one group's median perception differs from the others.

Statistical significance (p-value) alone does not convey the practical importance or magnitude of an observed difference. Therefore, for all comparative tests, an appropriate rank-based effect size was calculated. For the Kruskal-Wallis test, Epsilon-squared (ϵ^2) was used to measure the proportion of variance in the ranks explained by group membership. For the Mann-Whitney U test, the *rank-biserial correlation* (r) was calculated. These metrics provide a crucial, standardized measure of the size of the effect, independent of sample size.

In cases where a Kruskal-Wallis test yields a significant result, a post-hoc test is required to conduct pairwise comparisons and identify which specific groups differ. Dunn's test is the appropriate follow-up procedure as it maintains the rank-based structure of the Kruskal-Wallis test. Crucially, it incorporates a p-value adjustment to control for the family-wise error rate—the increased probability of a Type I error (false positive) that occurs when conducting multiple statistical tests simultaneously. In this study, the Holm-Bonferroni sequential correction method (Holm, 1979) was applied to all post-hoc pairwise comparisons. This method was deliberately selected over the standard Bonferroni correction because it provides the same rigorous defense against Type I errors while maintaining greater statistical power, thereby reducing the risk of Type II errors (failing to detect a true difference (Holm, 1979).

4.2.3.2 Relational Analysis

To accurately model the associations between the ordinal Likert-scale items, a polychoric correlation matrix was calculated. This technique is specifically designed for ordinal variables, as it assumes an underlying continuous latent trait for each ordinal variable and estimates the relationship between these latent traits, thereby avoiding the underestimation of the true relationship strength (Holgado–Tello et al., 2010; Olsson, 1979). In this study, the procedure estimates "thresholds" on this underlying normal distribution that correspond to the boundaries between the observed categories (1, 2, 3, 4). For each pair of variables,

it assumes that their two latent continuous variables follow a bivariate normal distribution. Using Maximum Likelihood Estimation, the algorithm finds the correlation coefficient (rho, ρ) for the underlying latent variables that is most likely to have produced the observed contingency table of two ordinal variables.

To reveal the latent structure within this matrix, an agglomerative hierarchical clustering algorithm (*hclust*) was applied to reorder its rows and columns. This data-driven process groups variables with similar correlation patterns together, causing conceptually related items to form visible blocks or "clusters" in the resulting heatmap visualization (Eisen et al., 1998).

4.2.3.3 Structural Analysis

We employed EFA to synthesize the complex web of correlations into a parsimonious model of the underlying latent constructs. EFA is a multivariate statistical technique designed to uncover the latent structure of a set of observed variables by identifying groups of items that are highly intercorrelated. EFA is based on the common factor model, which posits that the variance in any observed variable (z_i) can be partitioned into two components: Common variance (variance shared with other variables, attributable to the underlying common factors, F_m) and Unique Variance (variance specific to that variable alone, U_j). EFA represented by the equation:

$$z_i = a_{j1}F_1 + a_{j2}F_2 + \cdots + a_{jm}F_m + d_jU_j$$

Where factor loadings (a_{jm}) is the correlation between the observed variable and the latent factor (F_m), U_j represents the unique factor specific to that observed vảiable, and d_j represented the unique factor weight (Schreiber, 2021). The analysis was performed on the polychoric correlation matrix, the methodologically preferred approach for ordinal data (Holgado–Tello et al., 2010). The number of factors to retain was determined using Horn's Parallel Analysis, which compared the eigenvalues from the actual data to those from randomly generated data (Horn, 1965). This analysis provided an unambiguous recommendation to extract four factors. An oblique rotation (oblimin) was used, which allows the factors to be correlated—a realistic assumption for psychological constructs (Fabrigar et al., 1999).

Before conducting the analysis, two diagnostic tests were performed to assess the data's suitability: Bartlett's Test of Sphericity and the Kaiser-Meyer-Olkin (KMO) test. The first one evaluates the null hypothesis that the correlation matrix is an identity matrix (i.e. all variables are uncorrelated). For factor analysis to be viable, there must be patterned relationships to uncover, so this null hypothesis must be rejected ($\rho < 0.05$). The KMO test then assesses the proportion of variance among variables that might be common variance. The KMO statistic ranges from 0 to 1, with values greater than 0.60 generally considered the minimum threshold for a satisfactory factor analysis.

4.3 RESULT AND ANALYSIS

4.3.1 Nantes Nord gardeners' profiles

The initial analysis establishes a distinct and consistent profile of the gardeners in the 54 surveyed plots. As summarized in Table 4.3, the sample is predominantly composed of older adults; the largest age groups are 55-64 years (21 gardeners) and over 65 years (25 gardeners), meaning a remarkable 85% of the sample is aged 55 or older. The age-class thresholds utilized in this study (25-34, 35-54, 55-64, and over 65) were designed to reflect sociological life stages relevant to urban agricultural engagement, rather than strictly adhering to the standardized demographic brackets used by national census agencies such as INSEE. This socio-demographic categorization is calibrated to isolate distinct periods of time availability and lifestyle focus: young adults (25-34), established working-age adults facing peak professional and family time constraints (35-54), individuals in the transition to retirement (55-64), and fully retired individuals (over 65). As highlighted in urban gardening literature (Scheromm, 2015), the transition into retirement fundamentally alters time availability and frequently shifts the garden's function into a primary space for social identity and regular physical activity. Therefore, structuring the age classes around these lived realities provides a more functionally accurate foundation for analyzing the behavioral commitment observed within the community

Table 4.3. Profile of the Nantes Nord Gardener Community (n=54)

Demographic/Behavioural Variable	Frequency	Percentage
Gender		
Female	28	51.8%
Male	26	48.2%
Gardener status		
Association leaders	12	22.2%
Regular gardeners	42	77.8%
Age group		
25-34	1	1.9%
35-54	7	13%
55-64	21	38.9%
65+	25	46.3%
Daily time		
< 1 hour	3	5.6%
1 – 2 hours	8	14.8%
2 – 3 hours	21	38.9%
> 3 hours	22	40.7%
Weekly Frequency		
1-2 days per week	3	5.6%
3-5 days per week	31	57.4%
Everyday	20	37%

In terms of gender distribution, the sample comprises 28 female participants (~52%%) and 26 male participants (~48%). While initial survey parameters included occupational background, the resulting data was excluded from formal analysis due to incompleteness; however, the overwhelmingly older demographic distribution functionally serves as a reliable proxy, indicating a predominantly retired or semi-retired cohort. This demographic suggests that the allotment

gardens serve as important sites for post-retirement activity, social engagement, and well-being. Furthermore, the sample encompasses 12 association leaders (such as presidents, secretaries, and treasurers) and 42 regular gardeners. This composition ensures that the subsequent analysis captures both the administrative priorities of the governing boards and the everyday experiences of the general membership.

Engagement with the gardens is intense and represents a significant and regular time investment rather than a casual hobby. The size of the garden plot ranges from over 50m^2 to 190 m^2. The most common weekly frequency of visits is 3-5 days (31 gardeners), and the most common duration per visit is more than 3 hours (22 gardeners). The mean waiting time for a plot is 1.87 years, with a median of 1.5 years (**Figure 4.2**). This demand is not uniform across the city; gardens such as BR and EG exhibit significantly longer average waiting times (approximately 2.2 years). While extended waiting lists for urban green infrastructure are frequently interpreted in the literature as early indicators of eco-gentrification (Wolch et al., 2014), it is necessary to situate these sites within their specific urban gradient. Nantes Nord is a peripheral district characterized by a high density of social housing (37%) and is currently targeted for socio-economic urban renewal rather than experiencing advanced, market-driven gentrification. Therefore, the pressure on BR and EG stems from divergent operational and institutional realities rather than demographic displacement. For BR, the prolonged waiting time is

largely an administrative artifact; during the study period, the garden lacked a functioning association board, resulting in a governance bottleneck that stalled standard plot reallocation. Conversely, garden EG benefits from a highly active board and robust maintenance. Its extended waiting list reflects high localized demand for a well-governed allotment garden.

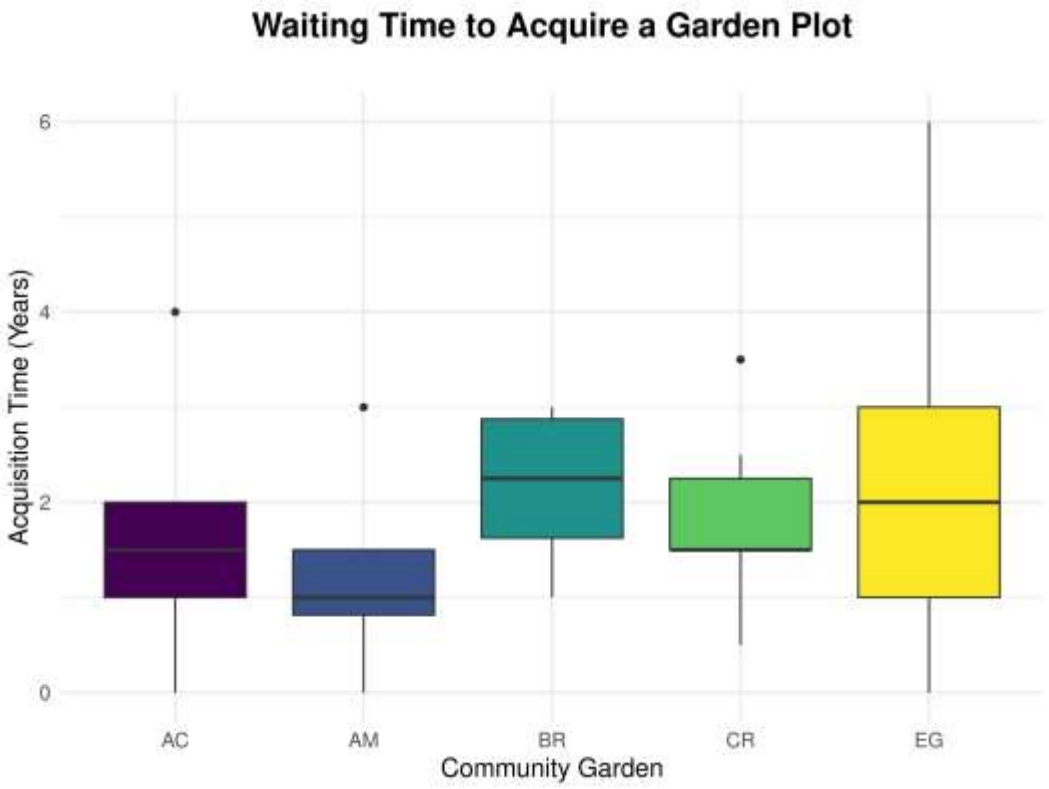

Figure 4.2. Average acquisition time for a garden plot in different gardens

Inferential tests revealed a lack of statistically significant relationships between these demographic characteristics and gardening behaviour. Mann-Whitney U tests showed no difference between male and female gardeners in terms of weekly visits ($p = 0.743$), or hours spent per visit ($p = 0.919$). Similarly,

Spearman's rank correlations found no significant association between age group and time commitment. The results suggest that the high level of engagement is a shared cultural norm within this community, independent of gender or age. This observation is consistent with a previous study investigating the psychosocial benefits of gardening in EC and AC, where gardeners expressed a similar view that gardens should be managed daily for high production (Sapin et al., 2023).

4.3.2 Perceived ecosystem services and disservices

The analysis of gardeners' perceptions through statistical analysis and audio records reveals a clear distinction between their views on benefits (ES) and their concerns about drawbacks (EDS). While the valuation of services is marked by high importance and strong consensus, the perception of disservices is characterized by a mix of specific, shared concerns and broad areas of deep disagreement.

4.3.2.1 Ecosystem services importance perceived by gardeners

There is a remarkably high and consistent appreciation for a wide range of ecosystem services. As shown in **Figure 4.3**, most bars that represent different ES are skewed heavily to the right, showing an overall positive sentiment towards ES perceived by the gardeners and high agreement that ES are “moderately” or “highly” important.

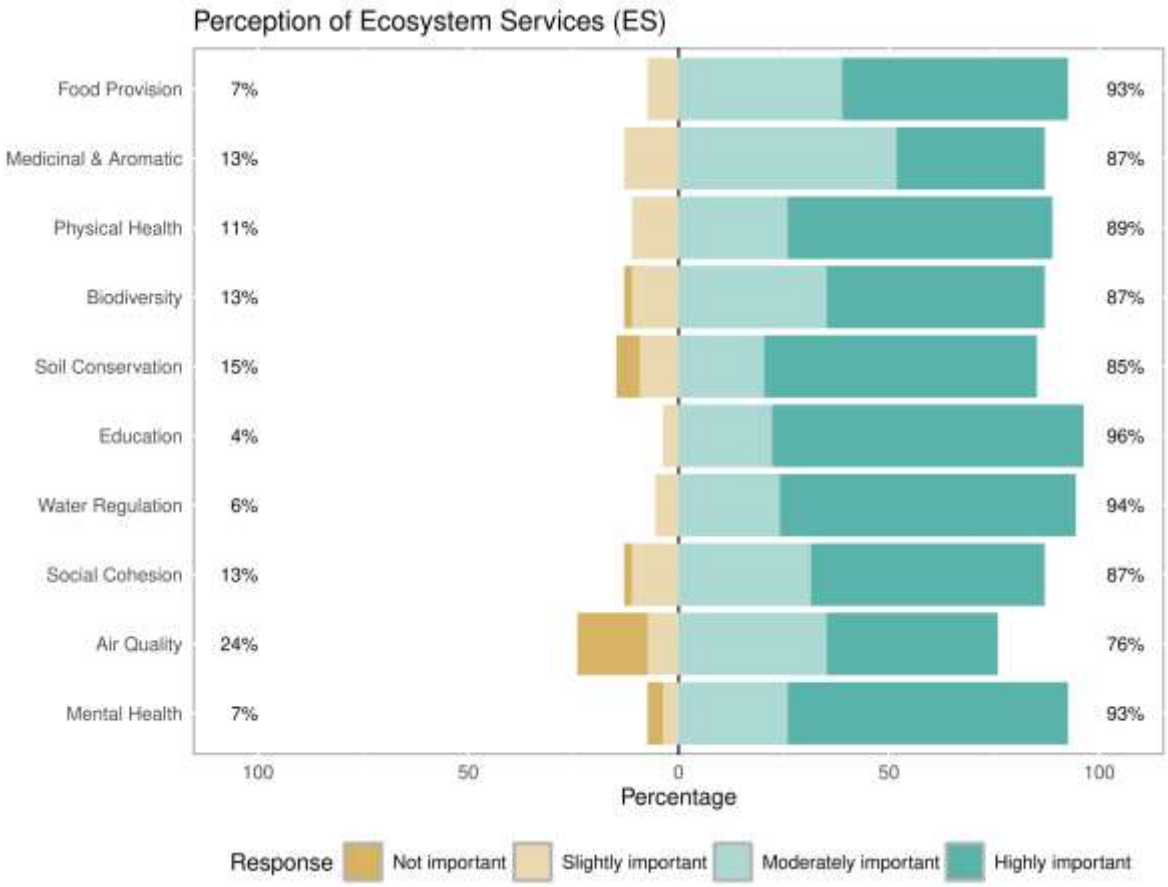

Figure 4.3. Distribution of gardeners' perceptions regarding the importance of 10 ES in Nantes Nord (n=54), measured on a 4-point ordinal Likert scale.

Table 4 shows a precise numerical summary of the results. An impressive seven out of the ten services have a median rating of 4 ("Highly important"), including *Food Provision*, *Physical Health*, *Biodiversity*, *Soil Conservation*, *Social Cohesion*, *Water Regulation*, and *Mental Health*. The low Interquartile Ranges (IQR) for these items, consistently at 1.00, signify a high level of consensus among respondents. This indicates a strong, shared belief that these services are of significant importance. The service of *Education* stands out as the most uniformly agreed-upon benefit, with a median of 4 and the lowest IQR of 0.75, suggesting a powerful

and near-universal belief in the educational value of the gardens. Gardeners often express their appreciation for learning about the plants' interactions with weather, insects, and each other during interviews. Over 74% of respondents rated *Education* as "Highly important".

Table 4.4. Collective Perceptions of Ecosystem Services

Ecosystem service	Not important (%)	Slightly important (%)	Moderately important (%)	Highly important (%)	***Median***	***IQR***
Food Provision	0,0	7,4	38,9	53,7	4	1
Medicinal & Aromatic	0,0	13,0	51,9	35,2	3	1
Physical Health	0,0	11,1	25,9	63,0	4	1
Biodiversity	1,9	11,1	35,2	51,9	4	1
Soil Conservation	5,6	9,3	20,4	64,8	4	1
Education	0,0	3,7	22,2	74,1	4	0,75
Water Regulation	0,0	5,6	24,1	70,4	4	1
Social Cohesion	1,9	11,1	31,5	55,6	4	1
Air Quality	16,7	7,4	35,2	40,7	3	1
Mental Health	3,7	3,7	25,9	66,7	4	1

Note: Responses were coded into a Likert scale system, with 1 = not important; 2 = slightly important, 3 = moderately important, 4 = highly important.

4.3.2.2 Ecosystem disservices' importance perceived by gardeners

In stark contrast, the landscape of concern over EDS is far more varied and reveals important areas of polarization. *Water Consumption* is the standout issue, being the only disservice with a median of 4 ("High concern") and a low IQR of 1.00, signalling a strong and widely shared worry about water usage. Conversely, a

strong consensus exists that several potential issues are not problems. Five of the eleven disservices have a median of 1 ("Not concerned"), including *Unpleasant Odour*, *Fear of Wilderness*, and *Air Pollution, Green Waste* (as shown in **Table 4.5**).

Table 4.5. Collective Perceptions of Ecosystem Disservices

Ecosystem disservice	Not concerned (%)	Low concern (%)	Moderate concern (%)	High concern (%)	***Median***	***IQR***
Food Contamination	22,2	24,1	25,9	27,8	3	2
Green Waste	55,6	11,1	5,6	27,8	1	3
Water Consumption	3,7	9,3	25,9	61,1	4	1
Water Pollution	44,4	7,4	11,1	37,0	2	3
Soil Pollution	37,0	9,3	9,3	44,4	3	3
Air Pollution	53,7	20,4	11,1	14,8	1	1,75
Allergies	51,9	5,6	24,1	18,5	1	2
Maintenance Cost	46,3	22,2	25,9	5,6	2	2
Pest/Insect Bites	38,9	18,5	18,5	24,1	2	2
Fear of Wilderness	59,3	14,8	22,2	3,7	1	1,75
Unpleasant Odour	66,7	14,8	13,0	5,6	1	1

Note: Responses were coded into a Likert scale system, with 1 = not concerned, 2 = low concern, 3 = moderate concern, 4 = high concern.

The most critical finding in this phase, however, is the evidence of division on other environmental issues. Items such as *Green Waste*, *Water Pollution*, and *Soil Pollution* all have extremely high IQRs of 3.00. For *Green Waste*, while the median response is "Not concerned" (1), the IQR of 3.00 indicates that the central 50% of respondents span almost the entire scale, from "Not concerned" to "High concern". This reveals a possibility of a highly polarized community on these topics, a finding that a simple measure of central tendency would have completely

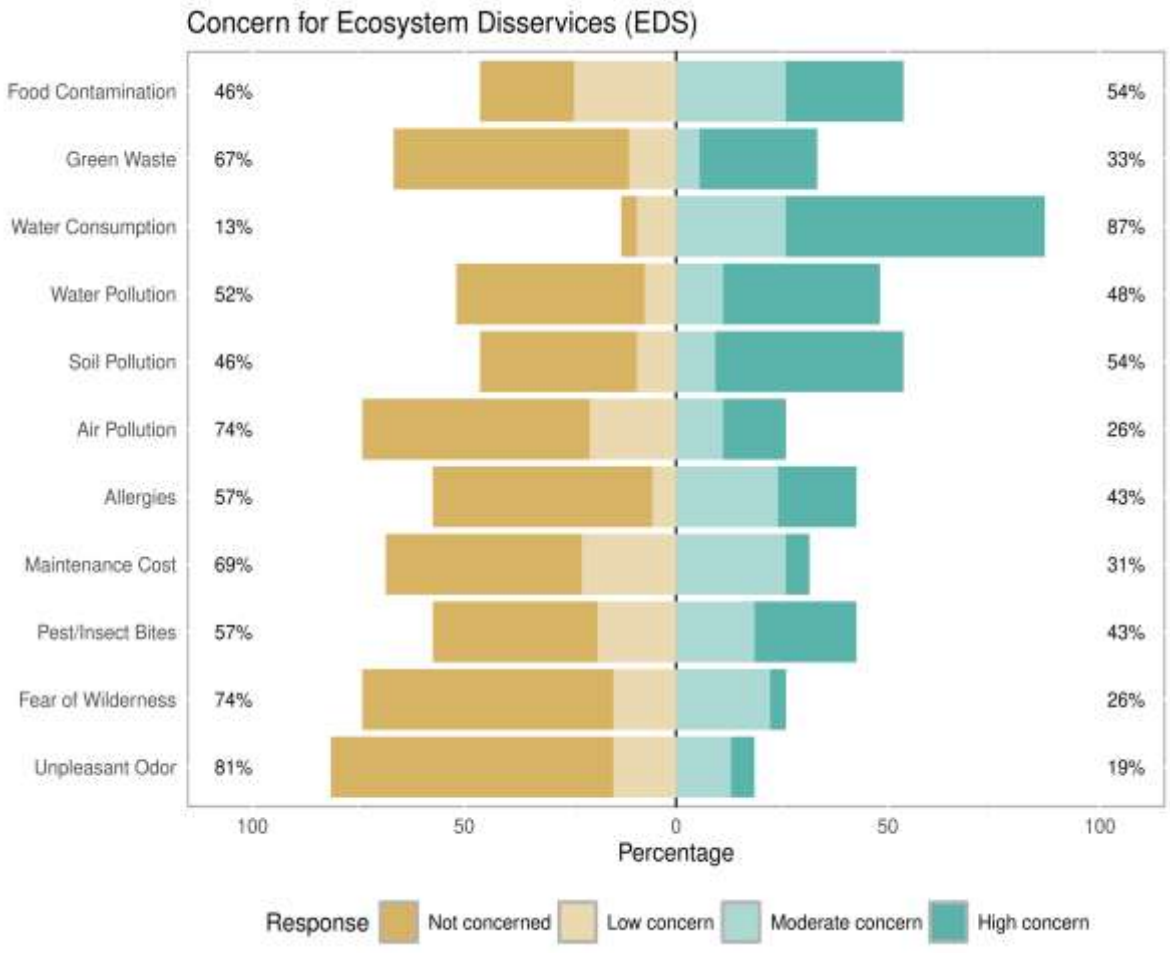

Figure 4.4. Distribution of gardeners' level of concern regarding 11 EDS in Nantes Nord (n=54), measured on a 4-point ordinal Likert scale

obscured (illustrated in Figure 4.4). Further discussion can be found in section 4.4.2.

4.3.2.3 Perception of ES and EDS across gardens

A series of Kruskal-Wallis H tests was conducted to determine if perceptions of the 21 ES and EDS items differed significantly across the five allotments garden sites. The tests yielded a clear and unambiguous result: there are no statistically significant differences in perception for any of the 21 items across the five different allotment garden sites (see Appendix A.2.6). All p-values were well above the 0.05 significance threshold, with the closest being for *Pest/Insect Bites* at $\rho = 0.06$. Furthermore, the calculated effect sizes were uniformly small or negligible, reinforcing the conclusion that the practical significance of any minor variations between gardens is trivial.

This consistency can be explained by several factors well-documented in urban ecological and sociological research. First, allotment gardeners are often a self-selecting group, drawn to the activity for similar reasons and from similar socio-economic backgrounds, leading to a pre-existing homogeneity in values regardless of the specific garden they join (Kingsley and Townsend, 2006). However, this might not be the case for all cities in France, such as Lyon(Deschamps 2025). Second, gardeners within a single city often participate in a shared culture, exchanging information and practices through social learning networks, which

leads to a convergence of beliefs (Krasny et al., 2014; Tidball and Krasny, 2007). Finally, the gardens are likely governed by a common municipal or institutional framework that standardizes rules and management practices, further minimizing site-specific differences (Colding and Barthel, 2013). The homogeneity result suggests that the physical locations of gardens in Nantes Nord do not seem to be a primary driver of how its members perceive its benefits and drawbacks. For Nantes Nord, other factors might be more influential across individual sites (e.g. shared gardening culture, common municipal oversight, or the self-selecting nature of the gardeners themselves)

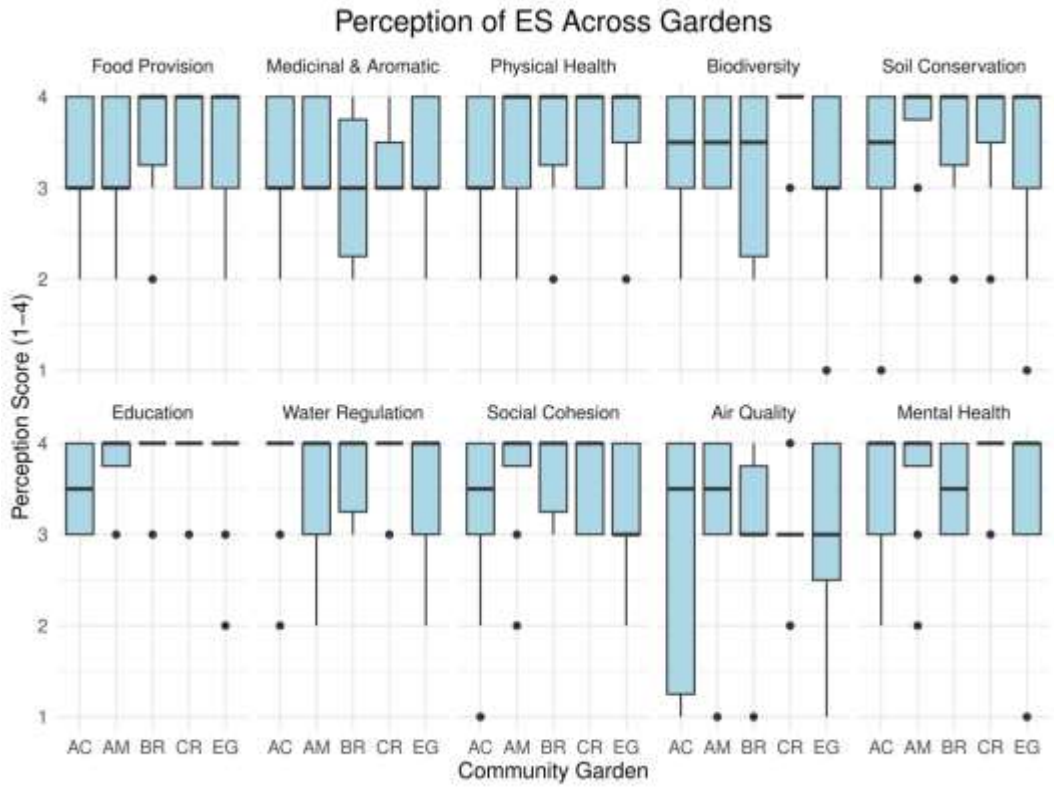

Figure 4.5. Box plots comparing the perceived importance of ES across the five studied allotment gardens (Angle Chaillou, Amande, Bruyères, Eglantiers, and Cressonière) using the Kruskal-Wallis H test

Figure 4.5 illustrates the perception scores for all of the ES from the Kruskal-Wallis H test across five gardens. The medians (darker horizontal lines) are all roughly at the same height, while the boxes (representing the middle 50% of responses) show a high degree of overlap. It reinforces the argument that the distribution of responses for any given item is nearly identical regardless of the garden site.

Similarly, Figure 4.6 shows a homogeneity across garden sites in the perceptions of gardeners towards EDS. Across 11 EDS, the box plots of different gardens show nearly identical medians (horizontal lines in each box) and heavily overlapping

interquartile ranges. The plots confirm the universal concern of *Water Consumption* in all study sites and portray a similarity in the low concern levels towards *Air Pollution*, *Unpleasant Odor*, *Fear of Wilderness*, and *Green Waste*.

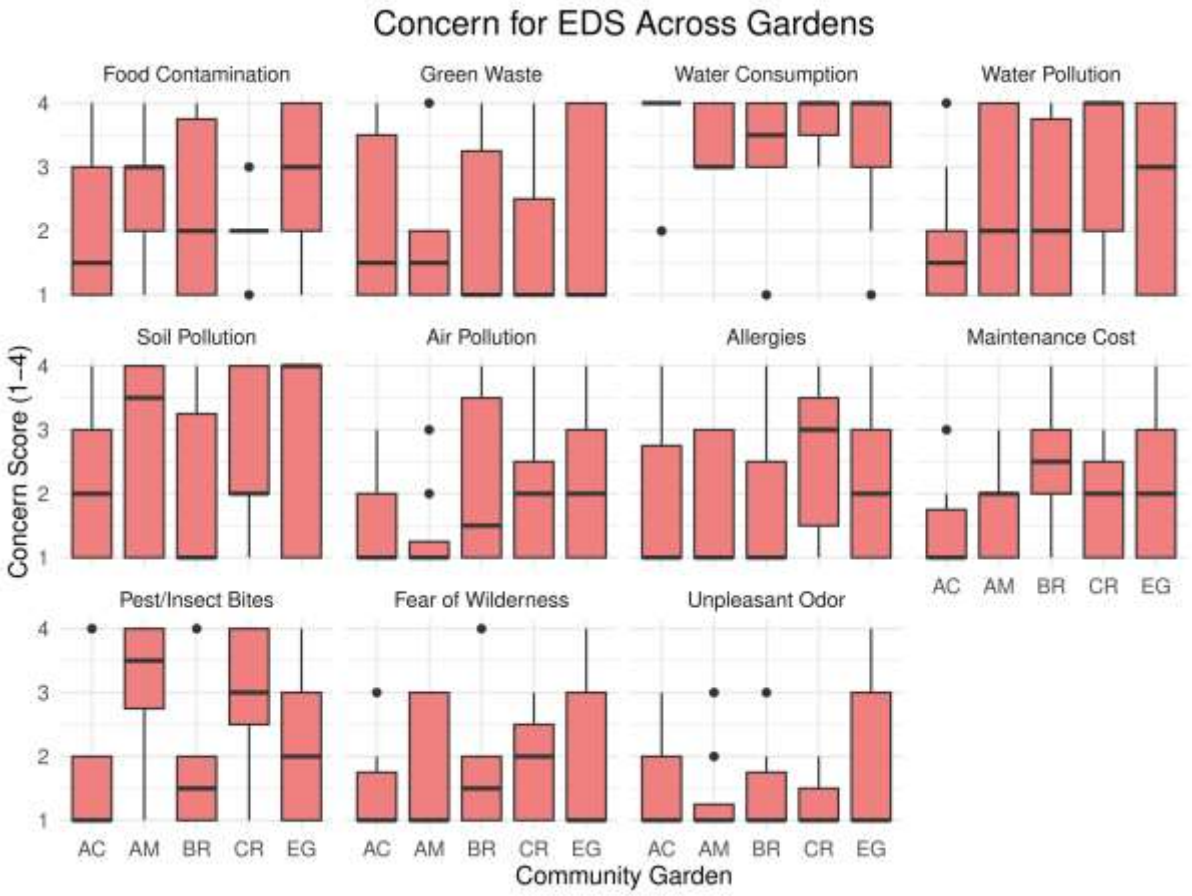

Figure 4.6. Box plots comparing the perceived concern for EDS across the five studied community gardens using the Kruskal-Wallis H test.

Among the ecosystem disservices, the concern for *Soil Pollution* emerges as a point of notable community division, evidenced by a highly polarized response pattern with an IQR of 3.00. While this polarization is present across the sample, it can be explained by a well-documented, site-specific issue at the EG garden, which has a

known history of trace element contamination. Notably, despite remediation actions undertaken by Nantes Métropole, gardeners at this site continue to express a high level of concern, illustrating the persistent psychological legacy of environmental contamination, where perceived risk can endure long after technical mitigation has been implemented

4.3.2.4 Perception of ES and EDS by gender

In sharp contrast, the Mann-Whitney U tests revealed that gender is a significant factor in shaping a specific, but not universal, subset of perceptions. Because ordinal Likert-scale data frequently masks distributional differences in visual representations (such as overlapping boxplots), the determination of significance in this study relied strictly on objective statistical thresholds rather than visual magnitude. While most views were shared across the sample, mathematically significant differences emerged for exactly five items. They are defined by yielding a $\rho - value$ below the strict 0.05 threshold and demonstrating at least a moderate rank-biserial effect size ($r > 0.30$). These significant variations fall into clear thematic categories related to care and risk (Figure 4.7 and Figure 4.8).

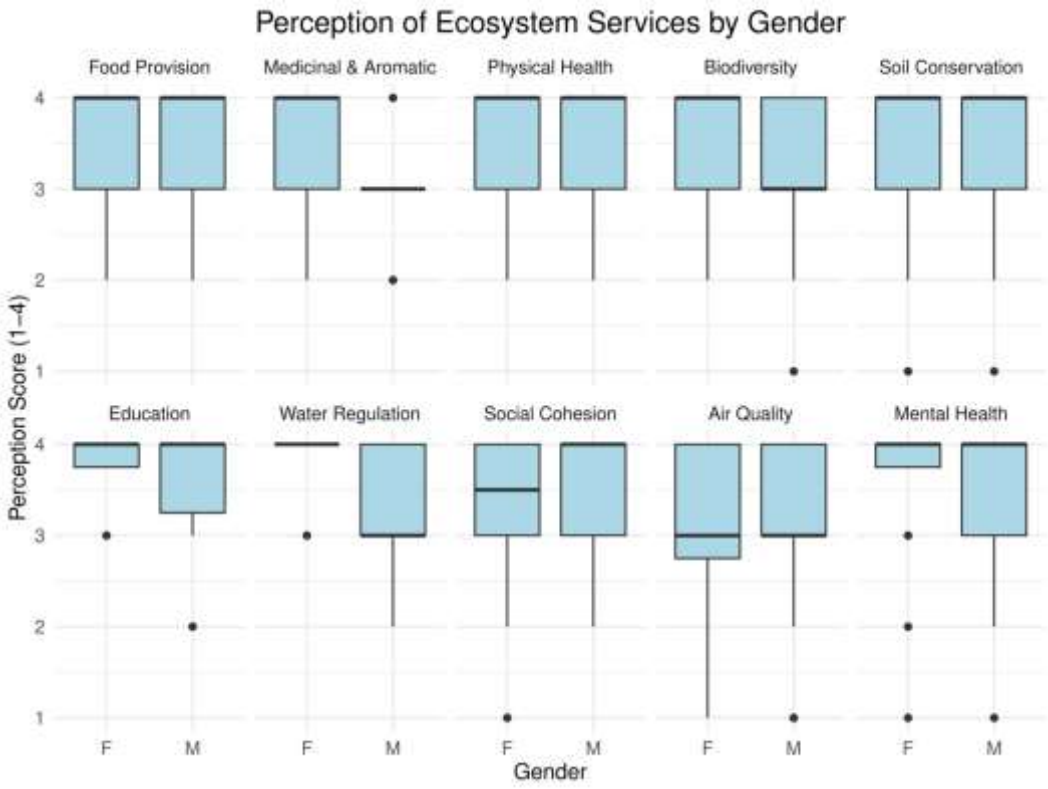

Figure 4.7. Comparison of perceived ES importance between female and male gardeners in Nantes Nord, utilizing the Mann-Whitney U test

Women were found to place a significantly higher value on services associated with an "ethic of care." The difference was most pronounced for *Medicinal & Aromatic* Plants, where the effect size was large ($r = 0.620$, $\rho < .00001$). A large effect was also found for *Water Regulation* ($r = 0.51$, $\rho = .00018$) and a moderate effect for *Biodiversity* ($r = 0.365$, $\rho = .0075$). This pattern rather reflects a socially constructed division of environmental labor. Women's heightened valuation of these specific services often correlates with their socially structured roles in managing family health, nutrition, and localized resource stewardship (Buckingham, 2020; Wut et al., 2021).

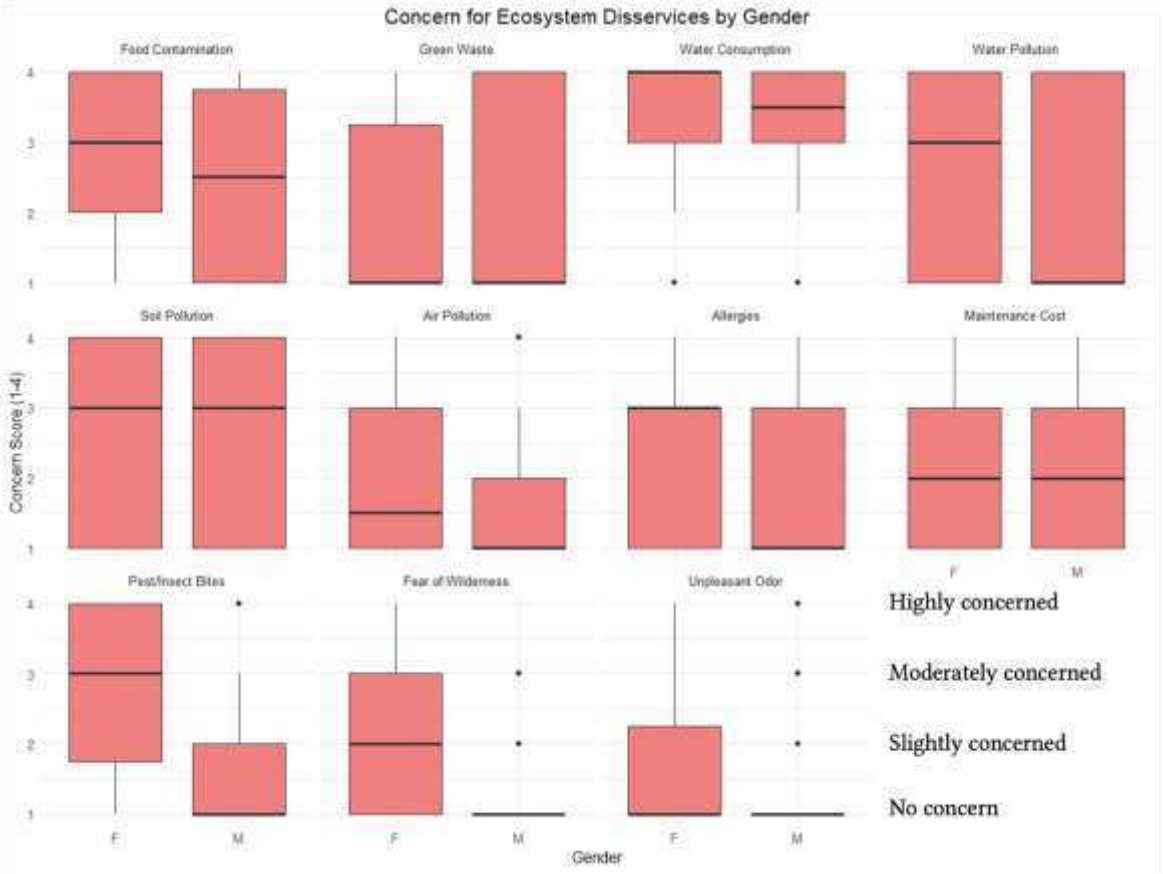

Figure 4.8. Comparison of perceived EDS concern between female and male gardeners in Nantes Nord, utilizing the Mann-Whitney U test.

Conversely, women reported significantly higher levels of concern for disservices related to localized environmental hazards (shown in Figure 4.8). Moderate effect sizes were found for both *Pest/Insect Bites* large ($r = 0.366$, $\rho = .00739$). *and Fear of Wilderness* large ($r = 0.363$, $\rho < .00782$). Details of the statistical summary are in Appendix A.2.7. This finding aligns with contemporary urban sociology, as women tend to navigate and experience urban spaces, including semi-wild green infrastructure, through a heightened awareness of safety and environmental risk, dictated by broader societal structures and disproportionate

responsibilities for dependents' safety (Beebeejaun, 2017; Skiba and Abramiuk, 2025).

It is equally important to note where no differences were found. Perceptions of core pragmatic items, such as *Food Provision*, *Maintenance Cost*, and the top concern of *Water Consumption*, were not significantly different between genders.

4.3.3 Synergies and trade-offs among ES and EDS

By employing a polychoric correlation matrix, we attempted to model the associations between these ordinal items, revealing the implicit structure of gardeners' beliefs, thus uncovering the latent connections between the 21 perception variables (Tobias 2019). Figures 4.10 and 4.11 visualize the correlation matrices of ES and EDS, respectively, as heatmaps. The strength of the correlation is indicated by the colour's intensity. Deep greens represent strong positive correlations, while deep red indicates strong negative correlations. White or pale colours signify a weak or non-existent relationship. The heatmap is dominated by several blocks of strong positive correlations, indicating that certain beliefs are conceptually linked in the gardeners' minds.

4.3.3.1 Synergies among the ES group and among EDS group

There is a strong positive correlation between the valuation of *Biodiversity*, *Soil Conservation*, *Water Regulation*, and *Education*, highlighted by a strong link between *Biodiversity* and *Soil Conservation* ($r = 0.74$). This correlation suggests that gardeners with a strong pro-environmental ethic perceive these services as integral components of a single, functional garden ecosystem. The tight coupling with *Education* ($r = 0.58$ with *Biodiversity*) indicates that these gardeners embody a "civic ecology" ethic (Krasny and Tidball, 2012), viewing the garden not merely as a space to conserve nature, but as a living pedagogy for understanding it (correlation matrix is illustrated in Figure 4.9)

A second, equally strong cluster connects *Mental Health*, *Physical Health*, and *Social Cohesion*. The strong correlation between mental and physical well-being ($r = 0.54$) confirms that gardeners experience these benefits holistically. It suggests that the physical act of gardening is inseparable from its stress-reducing mental benefits and that these are fundamentally mediated through community interaction. *Social Cohesion* is deeply integrated into this cluster, strongly correlated with both *Mental Health* ($r = 0.51$) and *Physical Health* ($r = 0.42$). The garden is a social prescription as much as an ecological one, reinforcing its role in building social capital.

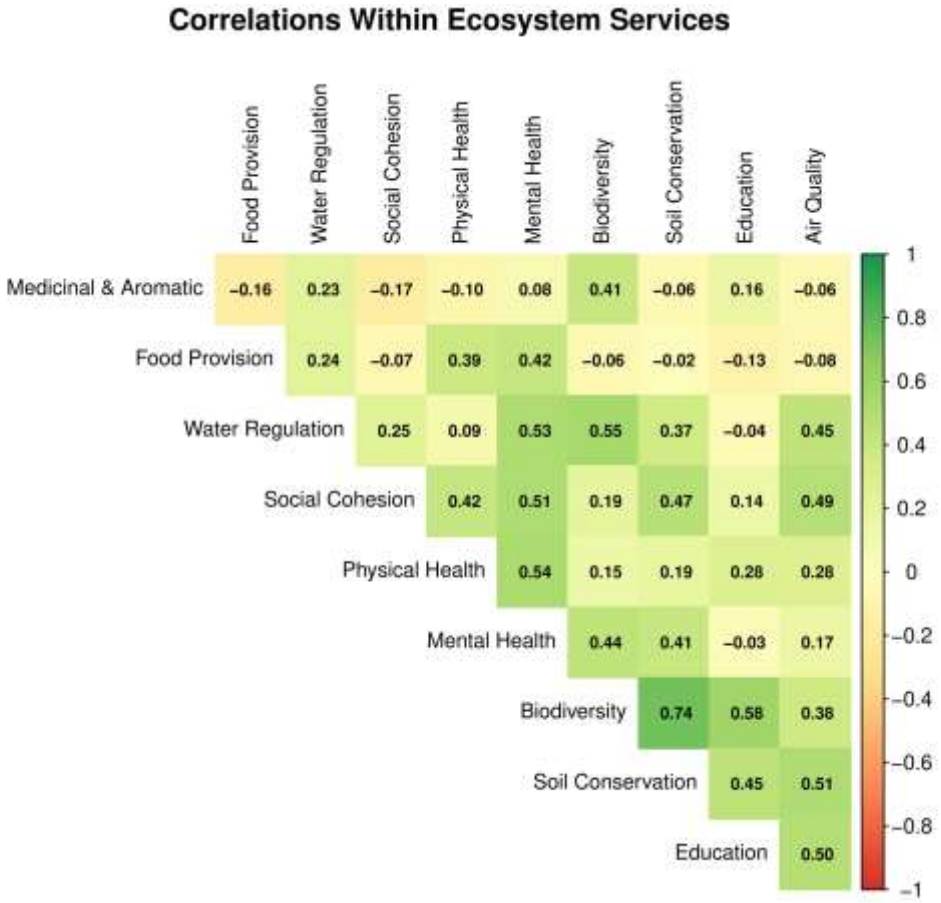

Figure 4.9. Heatmap of the polychoric correlation matrix illustrating the synergies (positive correlations) and trade-offs (negative correlations) among the 10 perceived ES.

Within the ecosystem disservices (Figure 4.10), a coherent cluster of concerns related to contamination is visible. Strong positive correlations link the anxieties around *Soil Pollution*, *Water Pollution, Air Pollution*, and *Food Contamination*. Among this group, the connection between *Water Pollution* and *Soil Pollution* is highest, with $r = 0.87$. It seems to indicate a generalized "contamination anxiety", since being concerned about one pollution pathway is likely to be concerned about others. Another less intense, positive correlation links *Allergies* to *Green Waste* and *Unpleasant Odour* ($r = 0.66$ and $r = 0.65$, respectively).

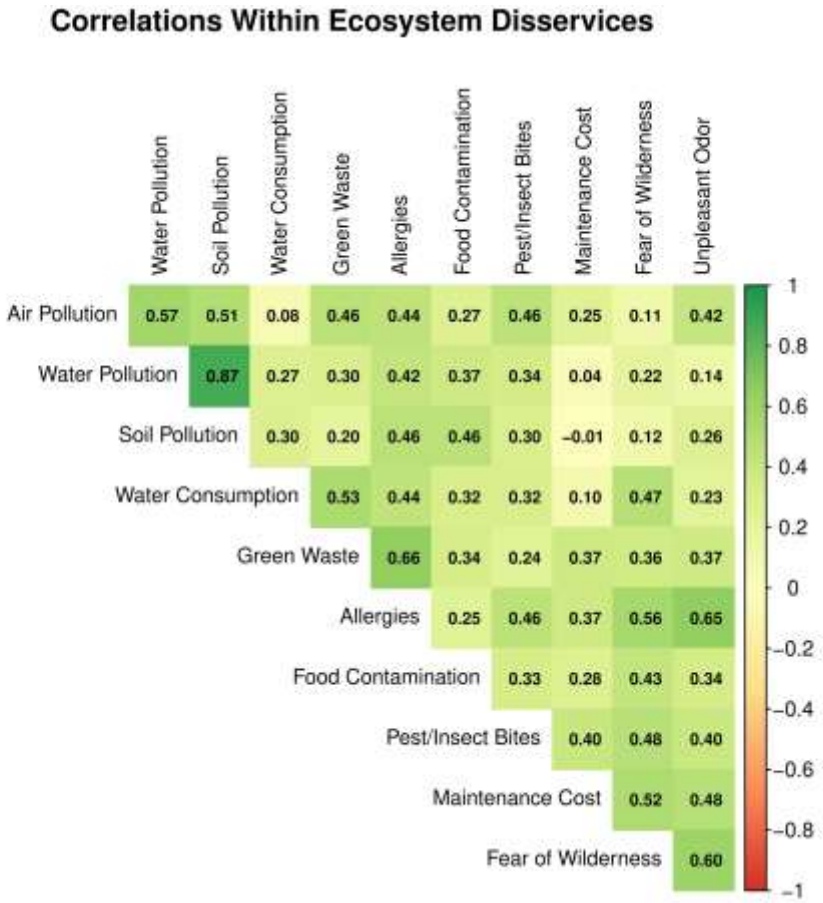

Figure 4.10. Heatmap of the polychoric correlation matrix illustrating the synergies and trade-offs among the 11 perceived EDS.

4.3.3.2 Synergies and Trade-offs between ES and EDS

While synergies dominate the belief system, the analysis of negative correlations is equally important, as it highlights the central conflicts that gardeners must navigate. Figure 11 presents the comprehensive heatmap of 21 ES and EDS (numeric data is presented in Appendix A2.8). The most critical trade-off identified in the data is the significant negative correlation between the value placed on *Food Provision* (an ES) and the concern towards EDS, such as *Water Pollution* ($r = -0.42$),), or *Soil Pollution* ($r = -0.31$). *Food Provision* is also negatively correlated

with concerns about *Green Waste* ($r = -0.33$) and *Allergies* ($r = -0.32$). This might reinforce the idea of a utilitarian focus. Gardeners prioritizing food production seem less troubled by issues of waste management or personal discomforts like allergies, possibly viewing them as secondary to the primary goal of the harvest.

A different type of trade-off appears between the benefits of community and health versus minor discomforts. There is a moderate negative correlation between the value of *Social Cohesion* and concern for *Unpleasant Odour* ($r = -0.30$). Similarly, a negative correlation exists between *Physical Health* and *Unpleasant Odour* ($r = -0.32$). This suggests that gardeners who highly value the social and health-related aspects of their plots have a higher tolerance for sensory nuisances. They may perceive things like the smell of compost or manure not as a problem, but as a necessary and acceptable part of a healthy allotment garden.

One of the interesting findings concerns the relationship between ecological values and personal comfort. The initial interpretation of this study suggested a potential trade-off, with a negative correlation expected between the value for *Biodiversity* and the concern for *Pest/Insect Bites* and *Fear of Wilderness*. However, the empirical data reveal the opposite: there are moderately strong positive correlations between *Biodiversity* and *Pest/Insect Bites* ($r = 0.45$) and between *Biodiversity* and *Fear of Wilderness* ($r = 0.46$). The correlations represent not a conflict but a synergy of tolerance and ecological literacy. It

suggests that the gardeners who most value a complex, biodiverse ecosystem are also more aware of, and accepting of, its "wilder" elements, including a wide variety of insects. This reflects a sophisticated eco-centric mindset where an appreciation for ecological complexity comes with an acceptance of its associated realities.

Finally, the analysis highlights how effective policy can resolve potential disservices. *Green Waste*, which was identified previously as a point of community polarization, is shown in the relational analysis to be correlationally isolated, with very weak links to other concerns. The existence of effective municipal composting and organic waste collection infrastructure has likely removed the problem of green waste disposal from the gardeners' network of anxieties, demonstrating how top-down structural support can eliminate a potential disservice at its source.

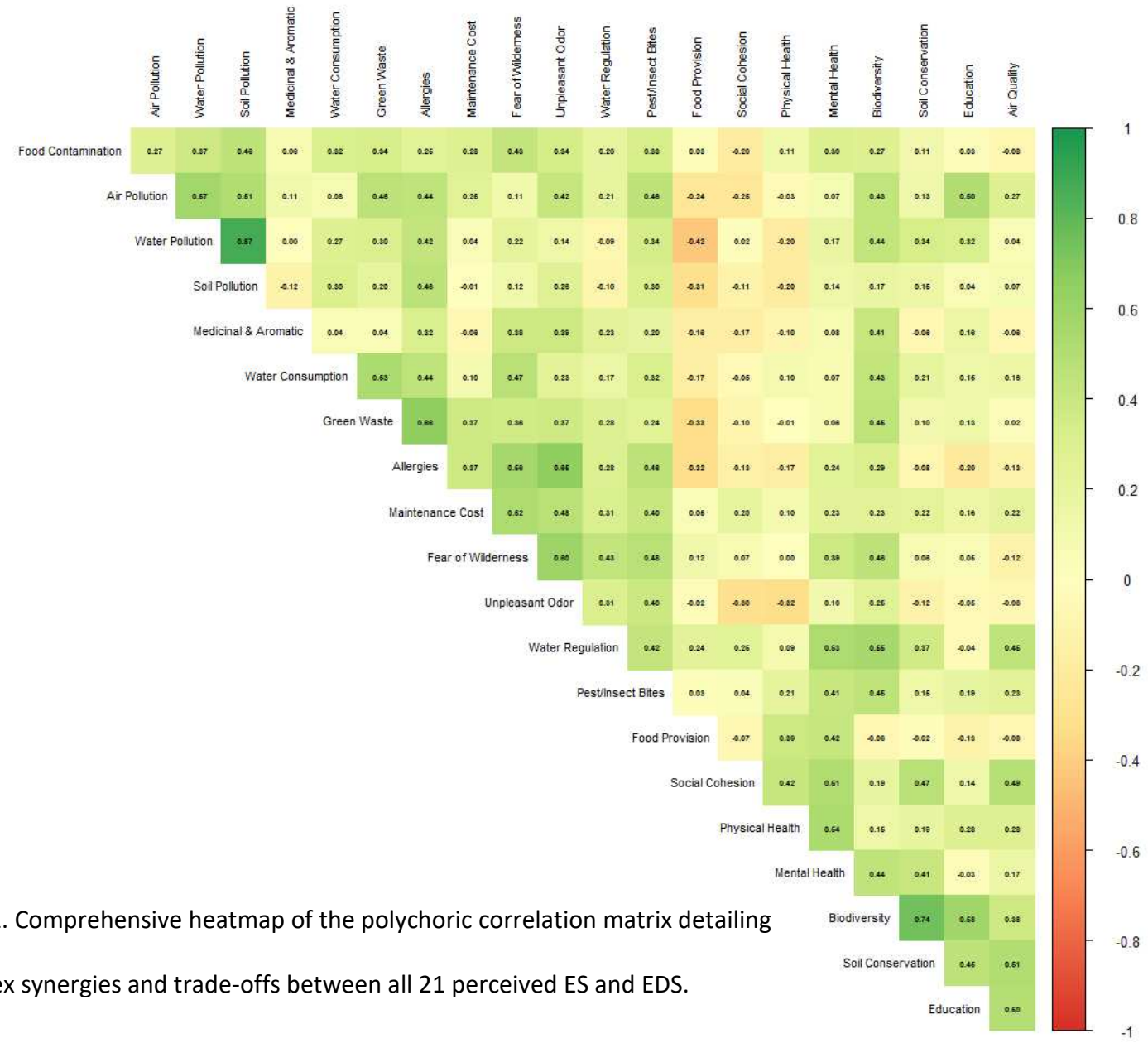

Figure 4.11. Comprehensive heatmap of the polychoric correlation matrix detailing the complex synergies and trade-offs between all 21 perceived ES and EDS.

4.3.4 Bundles of ES and EDS from urban gardens

The EFA extracted four distinct and conceptually coherent factors that collectively account for 56% of the total variance in the data. The low inter-factor correlations ($r < 0.27$) confirm that they represent relatively independent dimensions of perception. The final rotated factor loading matrix is presented in Table 4.6, with weak loadings suppressed for clarity (only loadings with an absolute value > 0.40 are shown for clarity; details are in Appendix A.2.9). While the extraction of these four latent factors is a mathematical procedure, the assignment of their descriptive nomenclature represents an interpretive, qualitative phase of the analysis. To move from numerical factors to conceptual bundles, each factor was named through an inductive thematic synthesis. The factors named by the underlying commonality shared by the specific variables that exhibited the highest primary factor loadings (typically >0.50) on that construct. This interpretive step bridges the abstract statistical output with the lived, phenomenological realities of the urban gardeners, resulting in the four named bundles detailed in Table 4.6.

Table 4.6. Rotated Factor Loading Matrix for Gardener Perceptions

Ecosystem services and disservices	**Factor 1: Nuisance**	**Factor 2: Ecological Stewardship**	**Factor 3: Pollution**	**Factor 4: Well-being**
Unpleasant Odour	0.85			
Allergies	0.76			
Fear of Wilderness	0.76			
Green Waste	0.53			

Medicinal & Aromatic	0.47				
Water Regulation	0.45				
Pet/Insect Bites	0.45				
Maintenance Cost	0.44				
Education		0.79			
Biodiversity		0.75			
Air Quality		0.68			
Soil Conservation		0.66			
Soil Pollution			0.98		
Water Pollution			0.91		
Mental Health					0.91
Physical Health					0.53
Food Provision					0.51
Social Cohesion					0.49

- **Factor 1 - Nuisance**: This factor is primarily defined by a collection of EDS related to the immediate, visceral experience of being in the garden. High loadings from *Unpleasant Odour* (0.85), *Allergies* (0.76), *Fear of Wilderness* (0.76), and *Pest/Insect Bites* (0.45) characterize it as a dimension of personal sensitivity to the less pleasant aspects of a semi-wild environment. The inclusion of *Maintenance Cost* (0.44) suggests that economic burdens are perceived as a form of practical nuisance, grouped with these other discomforts. The counterintuitive inclusion of two Ecosystem Services, namely *Medicinal & Aromatic Plants* (0.47) and *Water Regulation* (0.45), within this nuisance bundle is ecologically revealing. Mathematically, it reflects their positive correlation with these specific disservices in the raw data. It captures the reality of managing a 'complex'

or 'messy' garden ecosystem. Cultivating aromatic and medicinal plants (which are frequently allowed to flower and grow densely) and actively managing localized water regulation (such as maintaining open rainwater harvesting barrels or applying deep, decomposing mulch) physically increases a gardener's exposure to pollen (*Allergies*), standing-water insects (*Pest/Insect Bites*), and organic decay (*Unpleasant Odour*). Therefore, their loading on Factor 1 does not imply these services are nuisances themselves. Rather, it indicates that the practitioners who highly value and actively cultivate these specific ecological services are simultaneously the most intimately confronted by the, complex realities of a functioning, semi-wild urban garden.

- **Factor 2 - Ecological Stewardship:** This is a strong factor that perfectly aligns with the synergistic cluster identified in section 4.3.3. It is defined exclusively by high loadings from ES that represent an appreciation for the garden as a functional ecosystem: *Education* (0.79), *Biodiversity* (0.75), *Air Quality* (0.68), and *Soil Conservation* (0.66). This factor represents a coherent eco-centric worldview, where the garden is valued for its intrinsic ecological functions and its role as a space for environmental learning.

- **Factor 3 - Pollution:** This is the most statistically pure factor, defined by near-perfect loadings from *Soil Pollution* (0.98) and *Water Pollution* (0.91). It represents a singular, focused anxiety about chemical contamination in

the gardening environment. This concern is clearly distinct from the general "nuisance" of Factor 1, pointing to a specific awareness of and concern for anthropogenic pollutants.

- **Factor 4 - Well-being:** This factor clearly represents the direct, personal benefits gardeners derive from their plots. It is strongly anchored by *Mental Health* (0.91), with significant contributions from *Physical Health* (0.53), *Food Provision* (0.51), and *Social Cohesion* (0.49). This statistically demonstrates that gardeners perceive these benefits holistically, integrating the psychological, physical, social, and provisioning aspects of their experience into one coherent dimension of personal well-being.

The result from EEA suggests that urban gardeners' perceptions are organized along two primary axes of benefits (Ecological Stewardship and Personal Well-being) and two primary axes of concerns (Nuisance/Discomfort and Pollution).

4.4 DISCUSSION

4.4.1 Self-Selected Community of Practice

One of the most significant findings of this study is the remarkable homogeneity of perceptions across the five different garden sites. The lack of statistically significant differences suggests that the specific physical location or micro-culture

of an individual garden is not the primary determinant of how its members view its benefits and drawbacks. From the author's perspective, this result should not be seen as a failure to find a difference, but rather as a positive discovery of a shared view for Nantes Nord gardeners. The explanation for this homogeneity likely lies not in the gardens themselves, but in the social and administrative processes that populate them.

Allotment gardeners are not a random sample of the general population; they are a self-selecting group (D'Amore et al., 2026). If the demographic profile of gardeners interviewed in this study (i.e. predominantly older, highly committed individuals) was the general profile of Nantes Nord gardeners, it would then be consistent with findings from other Western cities that show allotment gardeners often share similar life stages and motivations (Grebitus, 2021). In Nantes, this self-selection is further structured by municipal policy. The official regulations for "*jardins familiaux*" stipulate that applicants must reside in Nantes and, critically, must not already own or rent a property with a garden. This policy effectively filters the applicant pool, selecting for individuals who lack private green space and are motivated enough to place their names on a waiting list that averages nearly two years.

This process creates a community of practice that is relatively homogeneous in its values and circumstances before its members even set foot in a specific garden. They share a common starting point: a compelling motivation for food production,

a strong desire for a connection to nature, and a willingness to invest significant time and effort to achieve it. This shared background and motivation appear to be a more powerful shaping force on perception than the unique characteristics of any single garden site. Research on urban allotment gardens has similarly found that overarching institutional frameworks are key in shaping their social and ecological outcomes, often leading to a convergence of practices and beliefs that minimizes site-specific differences (Colding and Barthel, 2013). Therefore, the homogeneity observed here is likely a direct reflection of a social system where demographic trends (an aging population seeking meaningful post-retirement activity) intersect with specific municipal policies that curate a community with a pre-existing shared ethos. While the perceptual homogeneity within Nantes Nord is significant, it is important to recognize that this uniformity is inherently bounded by the specific spatial and socio-economic scale of the district. If the analytical boundary were expanded across the entire metropolitan gradient of Nantes, encompassing highly contrasted neighborhoods ranging from affluent historic centers to diverse industrial peripheries, we would anticipate a significantly higher degree of perceptual heterogeneity. Contemporary urban ecology literature demonstrates that across broader urban gradients, varying socio-economic conditions, localized environmental stressors, and differing spatial constraints fundamentally alter how communities value green infrastructure (Camps-Calvet et al., 2016; Guo et al., 2024). For instance, comparative studies across diverse city zones frequently reveal that gardens in affluent neighborhoods are prioritized for

recreational and aesthetic cultural services, whereas those in lower-income or marginalized districts lean heavily toward utilitarian provisioning services, food security, and community empowerment (Guo et al., 2024). Furthermore, disparate environmental challenges between contrasted zones, such as varying exposure to urban heat islands or traffic noise, generate highly localized risk perceptions and divergent valuations of regulating services. Therefore, the homogeneity observed in this study represents a localized consensus shaped by the specific socio-economic realities and institutional framework of Nantes Nord, rather than a universal urban baseline. Future research aiming to map the complete socio-ecological metabolism of the city must account for this spatial variation across contrasted neighborhoods.

4.4.2 The Interplay of Governance and Grassroots Action

The perceptual landscape of the Nantes gardeners is not a static phenomenon but is actively co-produced by the dynamic interplay between top-down municipal governance and bottom-up civil society action. The data reveals specific patterns that can be understood by examining this interaction.

Gardeners in Nantes show a notably strong and consistent appreciation for a broad range of ES, especially those linked to health, nature, and community learning. The data highlights a clear consensus on these values. Seven out of ten

surveyed services received a median importance rating of 4, the highest score on a 4-point scale, meaning at least half the respondents regard them as "Highly important." These top services include *Physical Health, Biodiversity, Soil Conservation, Water Regulation, Social Cohesion*, and *Mental Health*. The low interquartile ranges (IQR) of 1.00 for most of these emphasize a shared and deeply rooted belief system. This pattern reflects more than just preferences; it mirrors the priorities built into Nantes' civic and political frameworks. The city's strategic plans and active local associations foster an environment where these benefits are promoted, experienced, and valued. For example, the importance given to *Social Cohesion* aligns with the city's participatory governance approach through the "*Dialogue Citoyen*" platform, which encourages collective action and engagement. Complementing this top-down effort are grassroots initiatives like MAAD, which aims to strengthen community ties through projects such as "*potagers solidaires*" (solidarity gardens). The organization itself is also receiving continuous support from Nantes Metropole for supporting initiatives towards social cohesion and solidarity. The high valuation of social cohesion relates to the lived experience within a civic infrastructure designed to support it. Similarly, appreciation for ecological services like *Biodiversity* and *Soil Conservation* supports Nantes' environmental objectives. he Projet Alimentaire Territorial seeks to develop food production that advances ecological transition. This goal is fundamentally reinforced by the national *Labbé Law* (effective January 1, 2019), which strictly prohibits the use of synthetic pesticides for non-agricultural and amateur

gardening across France. Consequently, municipal garden rules serve to actively enforce this national mandate at the local level ("*l'utilisation de produits phytosanitaires étant interdite*"), prompting gardeners to adopt natural, regenerative practices such as composting, companion planting, and fostering beneficial insects—activities that directly promote soil health and biodiversity. Their strong valuation stems from direct, practical engagement with practices mandated by city policies.

The most striking finding, however, is that Education has the highest level of consensus, boasting a median of 4 and an exceptionally low IQR of 0.75. This near-universal agreement on the educational value of the gardens is evidence of the success of a multi-level effort to frame these spaces as pedagogical tools. The city's official regulations explicitly state that a key objective of the gardens is to "*DÉVELOPPER une pédagogie*" (develop a pedagogy), particularly for children. This official mandate is brought to life by local associations like ECOS, which actively mobilizes the urban garden as a "*lieu d'échange, de créativité et d'apprentissage*" (place of exchange, creativity, and learning). ECOS offers a rich program of public courses and workshops on natural gardening techniques, wild plant identification, and seasonal cooking, transforming the gardens into living classrooms. The gardeners' perception that education is "Highly important" seems to be supported by training opportunities provided by the city's civic ecosystem.

For EDS, a notable example is the case of "*Green Waste*." The data for this item is anomalous: it has a low median concern of 1 ("Not concerned") but the highest possible IQR of 3, indicating extreme polarization. Furthermore, in the relational analysis, it is conceptually isolated, showing weak correlations with other disservice concerns. This pattern could be a direct reflection of successful municipal policy. The City of Nantes' regulations mandate composting and provide infrastructure for the collection of green waste, with the city itself responsible for emptying the collection bins. This top-down intervention has effectively solved the systemic problem of green waste disposal, "decoupling" it from the gardeners' network of anxieties about pollution or resource management. The residual polarization likely reflects individual-level disagreements over compliance or the tidiness of compost areas, rather than a systemic concern. This provides a powerful illustration of how effective governance can reshape gardener perception by designing a problem out of the system (Fox-Kämper et al., 2018).

On the other hand, despite municipal regulations that mandate the installation of rainwater collection tanks and provide access to tap water for irrigation, these top-down measures have evidently failed to resolve a strong concern surrounding water resources. Our data confirms this tension unequivocally: "*Water Consumption*" is the only ecosystem disservice to register a median of 4 ("High concern") with a low IQR of 1.00, indicating it is the most pressing and uniformly shared worry within the community. This concern manifests in practice,

particularly during the increasingly arid final months of summer, compelling many gardeners to rely on tap water to ensure crop survival. This behaviour creates a direct feedback loop, contributing to the disservice of "*Maintenance Cost*" as higher collective consumption translates into increased fees. As global climate change intensifies, regional projections for Pays de la Loire, where Nantes is situated, forecast a gradual yet consistent rise in average temperatures (Raisson-Victor et al., 2022). This escalating climatic pressure will inevitably place a higher demand on water resources, intensifying the strain on the food-water linkage. This dynamic is likely to amplify the conflict between the desire for productive harvests and the necessity of sustainable water use, posing a significant long-term challenge for both gardeners and municipal governance.

4.4.3 Navigating the synergies and trade-offs in the human-nature relationship

The relational analysis reveals the complex negotiations gardeners make between competing values. A particularly insightful finding is the moderate positive correlation between the value placed on *Biodiversity* and the concern for *Pest/Insect Bites* ($r \approx 0.45$). This counterintuitive result refutes a simple trade-off between ecology and comfort. Instead, this suggests that the gardeners who are most invested in the ecological health of their plots are also the most attentive to potential threats. This "informed concern" can be understood in several ways. First, a gardener actively cultivating a biodiverse plot is exposed to a greater variety of insect life, leading to a more realistic awareness of both beneficial organisms and potential pests. Second, this correlation may identify a highly engaged "steward" for whom valuing biodiversity and managing pests are two sides of the same coin of attentive management. Their concern is not a generalized fear, but a focused, managerial awareness of specific threats that could disrupt the ecosystem they are carefully cultivating.

This synergy of vigilance contrasts sharply with a more fundamental trade-off shown in the data. The analysis shows a significant negative correlation between the value of *Food Provision* and concern for *Water Pollution* ($r = -0.42$), a tension between utilitarian goals and abstract environmental concerns. It suggests that gardeners with a strong "productionist" mindset, who are highly focused on the

pragmatic goal of the harvest, tend to have a lower level of concern for broader, less immediate environmental issues. Their focus on yield may overshadow anxieties about the potential downstream impacts of their practices.

These dynamics are also inflected by gender. The finding that women report significantly higher concern for *Pest/Insect Bites* aligns with a large body of research on risk perception, which consistently finds that women often experience heightened awareness of risk related to health and personal safety. Because women often bear a disproportionate societal responsibility for community caregiving and family health management, their interaction with the garden requires a more acute, pragmatic vigilance regarding immediate biological hazards. herefore, their concern is less an expression of generalized fear and more a reflection of the practical, gendered realities of safely managing a complex, living ecosystem.

4.4.4 Limitations of this study

One of the primary statistical weaknesses of this study is the small sample size. The sample-to-variable ratio of approximately 2.5:1 (54 participants for 21 perception items) is below the conservative ideal of 10:1 (Watkins, 2018). This issue affected the EFA process, where the correlation matrix required statistical smoothing and was not positive definite. However, the data used in this study are part of a larger questionnaire that requires approximately 2 hours to complete;

thus, the author did not have the time to conduct more interviews. We follow Barrett and Kline's (1981) affirmation that a minimum of 50 observations could produce a clear, recognizable factor pattern. Future studies should aim for a larger sample size, which would produce a stable correlation matrix and support more complex modelling.

Furthermore, the high degree of behavioral homogeneity within the sample precluded certain multidimensional correlational analyses. Because over 94% of the surveyed gardeners visit their plots three to seven days a week, the dataset lacks the necessary variance in the 'frequency of use' variable to robustly correlate visitation rates with specific ecosystem service or disservice perceptions. Attempting to force a correlation matrix between these limited demographic/behavioral variables and the 21 distinct perception items on a sample size of 54 would mathematically inflate the family-wise error rate. Applying standard conservative adjustments, such as the Bonferroni correction, to control for these multiple testing comparisons would subsequently reduce the statistical power to a level where Type II errors (false negatives) become almost inevitable. Finally, while the survey quantified the volume of soil and water management practices, it did not record the vegetation typologies of the plants cultivated, limiting the ability to link specific crop selections to localized environmental perceptions.

Our sample is heavily skewed towards older adults (85% > 55 years old), in specific communities that are already motivated to participate in allotment gardening, which could affect the generalizability of the results. Future research could employ a stratified sampling strategy to capture a broader range of age groups, socio-economic backgrounds, and experience levels.

4.5 CONCLUSION

This comprehensive analysis has systematically deconstructed the complex worldview of 54 urban gardeners in Nantes Nord. Through a multi-phase statistical approach, we have moved from a broad description of the community to a synthesized and nuanced model of their underlying belief structures. The research demonstrates that the gardeners form a mature, highly committed, and behaviourally homogeneous community, whose perceptions are shaped more by their shared social identity and the overarching institutional context than by the specific location of their garden plot.

The entire system of 21 distinct perceptions of ES and EDS can be robustly summarized by a four-factor model. This model reveals that the gardeners' psychological reality is organized around four fundamental and largely independent constructs: (1) a concern for Nuisance, (2) a value for Ecological Stewardship, (3) a tension about Pollution, and (4) an appreciation for Well-being.

Ultimately, a granular understanding of the synergies and trade-offs between ecosystem services and disservices elevates urban green planning from a simple act of provision to a sophisticated practice of socio-ecological negotiation. By identifying synergies, such as the link between a concern for pollution and an appreciation for the ecosystem's regulatory functions, planners can design interventions that resonate with the community's existing mental models. Conversely, making trade-offs explicit is essential for avoiding policy failure, most notably the tension between fostering biodiversity and ensuring personal comfort. It forces a move away from one-size-fits-all greening strategies towards nuanced, co-designed solutions that proactively balance competing values, such as pairing habitat creation with improved pathway design or targeted ecological education. Furthermore, this analysis reveals that not all disservices are inherent. The case of *'Green Waste*,' a concern effectively neutralized by Nantes' municipal infrastructure, demonstrates that some of the most intractable conflicts can be 'designed out' of the system through targeted investment in resource management. This allows planners to distinguish between conflicts that require

CHAPTER 4 SUMMARY

- **Methodology**: Mixed-methods approach using semi-structured interviews and 4-point Likert-scale surveys across 54 garden plots. Analyzed via non-parametric statistics (Kruskal-Wallis H, Mann-Whitney U) and Exploratory Factor Analysis.
- **Key Results**: Extracted four distinct perceptual bundles characterizing the gardeners's view: Nuisance, Ecological Stewardship, Pollution, and Well-being. Proved that gardener perceptions are homogeneous across the study allotment gardens but vary by gender

5 THE FOOD-WATER-SOIL SUSTAINABILITY INDEX: AN INTEGRATED FRAMEWORK FOR ASSESSMENT AND GOVERNANCE

DISCLAIMER

This chapter is a novel contribution to the dissertation. It will be submitted to the *Nature-based Solutions* journal or *Ecological Modelling* journal, under the title "*Operationalizing the Food-Water-Soil Nexus: An Integrated Assessment Framework for Urban Garden Sustainability.*" The paper is authored by:

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Data and code availability

The dataset and all R scripts used for the statistical analyses presented in this chapter have been permanently archived. The materials are publicly available on GitHub and can be accessed at: https://doi.org/10.5281/zenodo.17538853

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ABSTRACT

This chapter operationalizes the Food Water Soil (FWS) nexus, engineering the FWS Sustainability Index as a diagnostic instrument for Urban Food Gardens. Prevailing urban agricultural assessments default to the Water Energy Food paradigm. The FWS framework elevates soil from a passive substrate to a foundational capital asset, recognizing pedological health as the central mediator of hydrological retention and caloric yield. The conceptual architecture appropriates the MESMIS methodology, discarding static, universal metrics in favor of context specific systemic attributes. Evaluation occurs through the dual lenses of core biophysical processes and the resultant Ecosystem Services and Disservices. The framework is empirically grounded via a case study in Nantes, France, where climatic vulnerabilities and municipal water reduction mandates dictate the functional weighting of the Food, Water, and Soil axes. This localized application transforms theoretical nexus interdependencies into a structural tool for adaptive urban governance.

5.1 INTRODUCTION

This dissertation has, in its preceding chapters, established the urgent need for effective, context-specific assessment tools to measure the performance and long-term viability of UFGs as a key form of NbS. As cities worldwide increasingly adopt UFGs to tackle a myriad of sustainability challenges, a significant gap persists between their widespread promotion and their evidence-based implementation. The preceding analysis has charted this gap, revealing a landscape of fragmented assessment methods and a dominant WEF nexus paradigm that consistently fails to adequately theorize the central, foundational role of soil in these unique urban ecosystems. In these specific contexts, energy is often a minimal input, while soil functions not as a passive substrate but as the foundational living infrastructure that mediates the system's core functions.

This systemic under-theorization of soil's dynamic role represents a critical gap in nexus research that this dissertation seeks to address.[1] In Chapter 3, I proposed and developed the Food-Water-Soil (FWS) nexus as a more fitting conceptual framework, one that repositions soil as the central mediating component—a capital asset whose health governs the interactions between water availability and food production. This chapter directly addresses the critical deficiency in assessment by presenting, justifying, and operationalizing a novel framework that translates this theory into practice: the MESMIS-FWS Sustainability Index.

This framework is specifically designed to be soil-centric, context-aware, and methodologically robust, offering a more relevant and accurate paradigm for evaluating the sustainability of soil-based urban ecosystems. It represents the culmination of the theoretical and empirical work presented earlier, translating the conceptual FWS nexus into a practical tool for strategic management and governance. The development of this index is not an arbitrary exercise; it is the synthesis phase of this dissertation's scientific method. It demonstrates how the theoretical work of Chapter 3 and the empirical investigation of stakeholder perceptions in Nantes from Chapter 4 converge to produce a tangible, applied output.

The chapter unfolds in a structured progression. It begins by deconstructing the conceptual architecture of the FWS framework, tracing its methodological lineage to the established MESMIS methodology and critically positioning it as a necessary evolution from the ill-fitting WEF nexus paradigm. The analysis then delves into the biophysical and social underpinnings of the urban FWS nexus, justifying the selection of specific indicators through the dual lenses of core ecological processes and the (ES and EDS they generate. The central challenge of indicator weighting is then addressed through an exhaustive analysis that integrates expert judgment with the empirically derived values of the Nantes gardener community. Finally, the chapter concludes by linking the assessment framework to an adaptive governance cycle, discussing its profound implications for fostering evidence-

based urban greening policies and promoting a more resilient approach to urban management.

5.2 CONCEPTUAL ARCHITECTURE FOR FWS

The development of a robust assessment framework requires a solid methodological foundation. The FWS Sustainability Index is not a creation *ex nihilo*; rather, it is a deliberate and critical adaptation of an established sustainability assessment methodology – the MESMIS method, re-engineered to address the specific ecological and social realities of UFGs. This section details this conceptual architecture, first by establishing its heritage in the MESMIS framework, then by critically interrogating the dominant WEF nexus paradigm to demonstrate its inadequacy, and finally by formally presenting the MESMIS-FWS framework as a necessary and superior alternative for this context.

5.2.1 Methodological Heritage from MESMIS

The FWS framework's methodological lineage is rooted in the Indicator-based Framework for Evaluation of Natural Resource Management Systems (MESMIS in Spanish). Developed in the mid-1990s for the context of peasant-managed Natural Resource Management Systems (López-Ridaura, 2002), MESMIS is more than a simple tool; it represents a comprehensive philosophical approach to sustainability assessment that is fundamentally systemic, participatory, and flexible (Astier et al., 2012). Its selection as the backbone for our framework was a deliberate choice, reflecting a deep alignment between its core philosophy and the nature of the system under study.

The core strength of MESMIS, and the primary reason for its adaptation here, lies in its use of systemic attributes to structure the evaluation. Instead of relying on a static checklist of indicators, MESMIS proposes that any sustainable system can be evaluated based on a set of seven fundamental dynamic properties: Productivity, Stability, Reliability, Resilience, Adaptability, Equity, and Self-reliance. These attributes provide a robust, scale- and discipline-independent foundation for evaluation, moving beyond a simple accounting of inputs and outputs to assess the deeper, functional characteristics of a system's long-term viability.

Operationally, the MESMIS methodology is structured as an iterative, six-step evaluation cycle designed for continuous learning and adaptive management:

1. System Definition: Characterizing the system to be evaluated, its components, and its socio-environmental context.

2. Identification of Critical Points: A diagnostic step where relevant actors collaboratively determine the key factors or processes that enhance or constrain the system's sustainability attributes.

3. Selection of Strategic Indicators: Deriving and selecting case-specific indicators that are linked to the critical points and the overarching sustainability attributes.

4. Measurement and Monitoring: Assessing the selected indicators using a variety of quantitative and qualitative methods. Integration and

5. Presentation of Results: Synthesizing the information from diverse indicators, often using graphical tools like "amoeba" diagrams to compare the strengths and weaknesses of different systems.

6. Conclusions and Recommendations: Formulating recommendations for improving the system, which then initiates a new evaluation cycle.

This cyclical, "spiral" process contrasts sharply with static evaluation methods and aligns perfectly with the continuous learning loop required for the adaptive management of complex social-ecological systems like UFGs. The inherent participatory ethos of MESMIS is a direct philosophical match for the nature of

UFGs. The methodology presupposes the importance of user perception, a premise that the empirical data from the Nantes case study in Chapter 4, which revealed the profound influence of gardeners' values and social dynamics, later confirms.[1] A purely top-down, expert-driven assessment framework would represent a methodological mismatch for the system being studied; the choice of MESMIS, therefore, reflects a pre-emptive alignment of methodological philosophy with the social reality of UFGs.

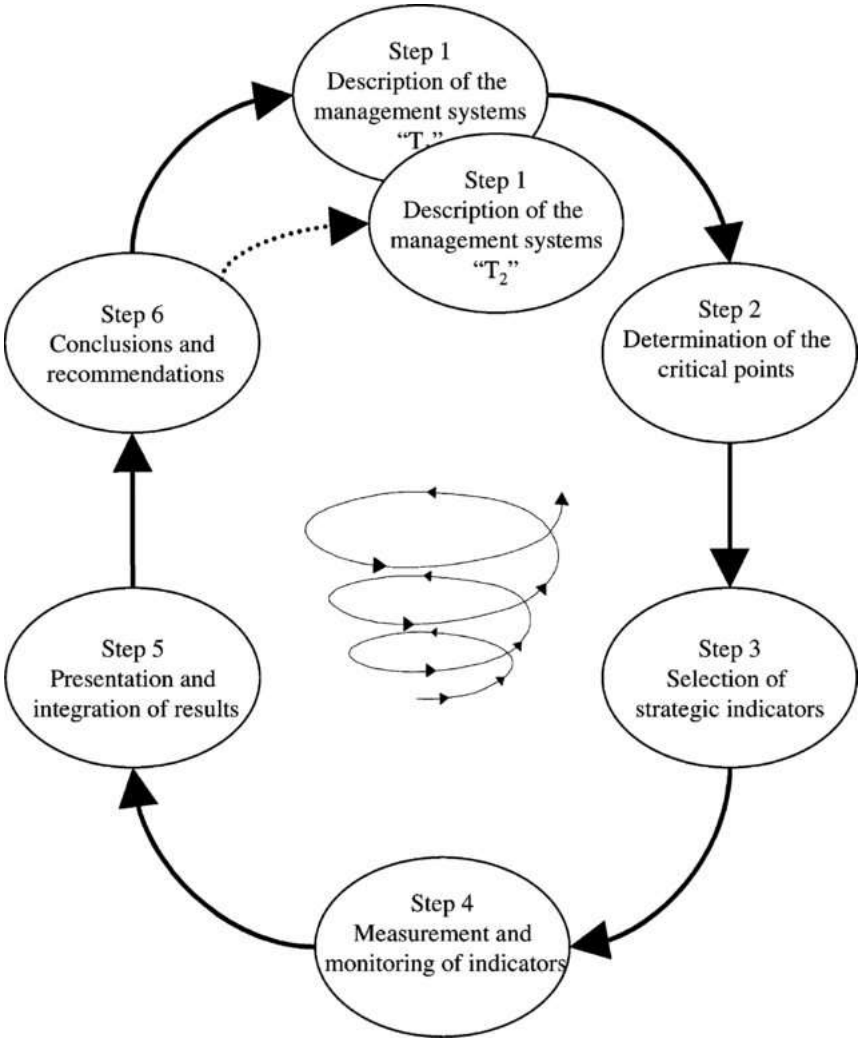

Figure 5.1 The MESMIS evaluation cycle

Notably, MESMIS has demonstrated its methodological flexibility, particularly its successful adaptation for nexus assessment. The "Nexus Pampa" project, for instance, replaced the traditional MESMIS traid of social, economic, and agro-ecological dimensions with the axes of the WEF nexus (Viana et al., 2023). This act of substitution reveals the process-oriented, not content-specific nature of the

MESMIS framework. The framework provides a promising pathway for operationalizing nexus thinking because it is designed from the ground up to be context-specific. The process begins not with a fixed set of universal indicators, but with the participatory identification of a system's unique "critical points". The dimensions and indicators are then selected to address these specific points. Our adaptation of MESMIS for the FWS nexus is a principled application of its core philosophy. It involves using its structured, participatory process to build a set of dimensions (Food, Water, Soil) and corresponding indicators that are precisely tailored to the unique critical points of UFGs that we have identified throughout this research.

5.2.2 WEF Nexus to the Soil-Centric FWS Nexus

The WEF nexus concept has provided a powerful and influential paradigm for understanding large-scale resource security challenges. Originating from high-level policy discussions, its primary utility has been in addressing cross-sectoral interdependencies at national and transboundary levels. However, as with any powerful concept, its application across different scales and contexts requires careful consideration. When applied to the hyper-local, socially embedded ecosystem of an urban garden, the WEF framework reveals critical limitations that necessitate a context-specific adaptation.

A primary consideration is the issue of scale. The WEF nexus was largely conceived to analyse and govern massive, formalized resource flows through national grids and river basins. This macro-scale, flow-based logic is not a natural fit for the small-scale, often informal resource dynamics of a allotment garden, where resource flows are mediated by social relationships as much as by infrastructure. Perhaps the most significant reason for adaptation, however, is the treatment of ecosystems. In many WEF frameworks, the environment and soil are positioned as external factors or as an additional, sometimes secondary, component (see chapter 2). This approach, while valid in some contexts, does not fully capture the reality of soil-based systems like UFGs, where the ecosystem is not an add-on but the foundational living infrastructure upon which the entire system depends.

The FWS nexus is therefore proposed not as a rejection of the WEF paradigm, but as a logical and necessary re-grounding of nexus thinking for the specific context of soil-based, low-energy urban ecosystems. The conceptual shift is straightforward yet significant: it replaces the **'Energy'** component with **'Soil'**.[1] The core innovation of the FWS nexus is its reframing of soil not as a simple resource *flow* but as a *capital asset*.[1] The health of soil is a qualitative state that is determined by the system's capacity (i.e. interactions between physical, chemical, and biological properties) to perform its functions. This is why traditional nexus models based on material flow analysis are often insufficient; the critical resource to manage is not soil mass, but soil health, a complex quality that cannot be

captured by a single metric. This reframing necessitates a move towards a performance-based assessment that evaluates the quality of the system's functioning, a task for which the MESMIS framework was developed.

5.2.3 MESMIS-FWS Framework Adaptation

Our adaptation of MESMIS for the FWS nexus is a principled application of its core philosophy. Building upon the methodological flexibility and the precedent of integrating a nexus-based dimensional framework established in Section 5.2.1 (Viana et al., 2023), the MESMIS-FWS framework introduces a fundamental structural adaptation. Rather than replicating the WEF nexus axes, we substitute the broad evaluative dimensions with the specific, interconnected axes of our proposed nexus—Food, Water, and Soil. This creates a hybrid framework that is both methodologically robust and theoretically coherent with the dissertation's central thesis. The logical justification for this shift from 'Energy' to 'Soil' is rooted in the specific context of UFGs. In these systems, external energy inputs are often minimal, whereas the biophysical interactions between soil quality, water cycles, and plant growth are the dominant drivers of the system’s productivity, resilience, and overall sustainability.

Building upon this precedent, the MESMIS-FWS framework involves a fundamental adaptation: the substitution of MESMIS's broad evaluative dimensions with the specific, interconnected axes of our proposed nexus—Food,

Water, and Soil. This creates a hybrid framework that is both methodologically robust and theoretically coherent with the dissertation's central thesis. The logical justification for this shift is rooted in the specific context of UFGs. In these systems, external energy inputs are often minimal, whereas the biophysical interactions between soil quality, water cycles, and plant growth are the dominant drivers of the system's productivity, resilience, and overall sustainability. The FWS framework is thus tailored to this reality, providing an analytical lens that aligns with the system's actual ecological and physiological dynamics. Table 5.1 summarizes this conceptual evolution, illustrating the distinct logic and application of each framework.

Table 5.1. A comparative analysis of sustainability assessment frameworks

Feature	**MESMIS Framework**	**NEXUS-MESMIS (WEF)**	**Food-Water-Soil (FWS) Nexus**
Core Dimensions	Social, Economic, Environmental	Water, Energy, Food	Food, Water, Soil
Central Logic	Balancing the three pillars of sustainability	Managing interdependencies and trade-offs between sectors	Mediating food production and water cycles through soil health
Typical Application	Rural/Peasant Natural Resource Management Systems (NRMS)	Regional/National resource security (e.g. river basins)	Soil-based, low-energy agroecosystems (e.g. urban gardens, valley and mountain grassland)
Treatment of Soil	A component of the 'Environmental' dimension	Often externalized as 'Land' or a passive substrate	A central, dynamic, and mediating capital asset

Feature	MESMIS Framework	NEXUS-MESMIS (WEF)	Food-Water-Soil (FWS) Nexus
Primary Output	A holistic sustainability assessment (radial chart)	Optimization of resource allocation across sectors	Assessment of socio-ecological resilience and performance

5.3 APPLICATION OF THE MESMIS-FWS EVALUATION TO NANTES

5.3.1 Context of the case study

The city of Nantes serves as the administrative capital of the Pays de la Loire region in western France. As the nation's sixth-largest city by population, with 325,070 inhabitants recorded in 2022 (Insee, 2025b), it is the principal municipality within the Nantes Métropole administrative area. The city is geographically defined by its location along the confluence of the Loire, Erdre, and Sèvre rivers, a feature that has historically shaped its development and continues to define its extensive network of green corridors. Nantes has a long-standing reputation for horticultural and botanical activities. The city was named the European Green Capital in 2013. It is a cultural heritage that provides a strong precedent for its contemporary commitment to urban greening policies and active public engagement in nature-based initiatives. The specific study area is Nantes Nord, a district situated in the northern part of the municipality, covering an area of approximately 7.6 km^2 (760

hectares). This district is a critical focal point for understanding the dynamics of urban green infrastructure due to its unique socio-ecological composition.

Until the 1950s, the territory of Nantes Nord remained largely rural, serving as a leisure area for the city's inhabitants with farms, horse racing, and riverside taverns. The post-World War II period, however, brought a dramatic transformation. Driven by a national housing shortage, French urban policy shifted away from subsidizing single-family homes towards the rapid construction of large, dense, collective housing complexes, known as "*grands ensembles*". Nantes Nord, with its available agricultural land reserves, became a primary site for this development. The construction occurred in two main waves, from 1957 to 1962 and again from 1969 to 1976, resulting in the creation of major social housing estates such as La Boissière, Petite Sensive, Bout-des-Pavés, and Chêne-des-Anglais (Francis, 2007).

Nantes is characterized by a temperate marine west coast climate (Köppen classification: Cfb), with mild, wet winters and warm, relatively dry summers. The average annual temperature is approximately 12°C, with monthly averages ranging from around 6°C in winter to 20°C in summer. In recent years, the highest temperature has reached 38°C in August. Precipitation is distributed fairly evenly throughout the year, totalling approximately 788 mm annually (Raisson-Victor et al., 2022). There is, however, a discernible seasonal pattern, with the wettest period occurring from October to January and the driest month typically being

July. While the region receives ample rainfall on an annual basis, the relative dryness of the summer months coincides with the peak growing season for vegetable gardens, creating a potential need for supplemental irrigation.

This climatic reality provides a crucial context for one of the key findings from the survey of local gardeners: "*Water Consumption*" was identified as their single greatest concern. This perception of water as a potentially scarce or precious resource, despite the region's overall wet climate, highlights the temporal mismatch between natural supply and agricultural demand. Gardeners are acutely aware of the need for water during the summer to ensure the productivity of their plots, a concern that is likely heightened during periodic dry spells or heatwaves, which appear more common in recent years. This bottom-up perception of water scarcity must be analysed in conjunction with top-down policy pressures. At a national level, France is actively addressing the challenges of climate change and increasing water stress through its comprehensive "Plan Eau 2023-2030" (Ministères Aménagement du territoire Transition écologique, 2023). A central and ambitious target of this plan is to achieve a 10% reduction in total water abstraction across all sectors by 2030. This national policy imperative signals a strategic shift towards water conservation and efficiency.

While no specific plan for the city of Nantes was identified in the available documentation, the city and its metropolitan authority are undoubtedly tasked with contributing to this national goal. At the district level, the "Projet Global

Nantes Nord" is the primary operational strategy for urban renewal. Launched in 2016, this project explicitly aims to leverage the district's green spaces to address its social challenges, with a strong focus on improving social cohesion and public tranquillity. This local effort is amplified by Nantes' participation as a frontrunner city in the EU-funded URBiNAT project, which has provided both funding and a methodological framework for implementing a "Healthy Corridor" through a process of community co-creation. These top-down initiatives create a highly supportive institutional environment for allotment gardens, viewing them as key components of the broader urban regeneration strategy.

The City of Nantes has a well-defined policy for managing its collective gardens. The city distinguishes between three types: *jardins familiaux* (individual allotment gardens), *jardins partagés* (communally managed shared gardens where harvests are shared), and *potagers solidaires* (solidarity gardens where produce is grown for food aid distribution). The operation of these gardens is formalized through a city-wide regulation, *Le règlement des jardins collectifs*, and various charters, such as the *Charte des jardins collectifs* and the broader *Charte des arbres*. These documents establish a formal relationship between the city and the gardening associations, outlining the respective commitments. The city typically provides the land and may offer technical support, while the associations and their members are responsible for day-to-day management, adherence to ecological practices (e.g. prohibition of synthetic pesticides), and maintenance of the plots and

common areas. This structured, policy-driven approach provides a clear institutional framework that supports and regulates the activities of the allotment gardens.

A significant element underpinning the entire allotment garden system in Nantes Nord is the security of land tenure. The analysis of the district's land registry indicates that the open spaces where gardens are located are predominantly public property, belonging either to the City of Nantes, the metropolitan authority, or the social housing landlords. The allotment gardens exist not on precarious, temporarily available private land, but on publicly controlled land allocated for this purpose through a formal policy framework. In total, there are 5 allotment gardens (*les jardins familiaux*) situated in Nantes Nord (refer to Figure 4.1). The data used in this study were collected in all 5 gardens.

Additionally, the challenge of soil quality is a central and complex issue for urban gardening in Nantes, as municipalities must contend with the reality of heterogeneous urban soils often impacted by past human activities. Research conducted in the region's urban gardens has specifically identified trace metal elements, particularly lead (Pb) and arsenic (As), as a primary concern (Bechet et al., 2018) – particularly at EG garden. However, this contamination can also be "geogenic", meaning it is likely to originate from the natural parent rock rather than from industrial surface deposits (Jean-Soro et al., 2015). Studies have confirmed that soils in Nantes allotment gardens are "moderately enriched by Pb

from geogenic origin," with analyses showing that concentrations of these elements increase with soil depth. Despite this natural origin, concentrations of metals like Pb and cadmium (Cd) have still been measured at levels higher than the maximum permissible limits for agricultural soil set by the WHO/FAO, which are established at 60 mg/kg for Pb and 3 mg/kg for Cd (Feyisa et al., 2025; Jean-Soro et al., 2015). The primary concern associated with these elements is their potential translocation into edible plants, a risk confirmed by research identifying the "presence of lead in some vegetables". This risk is crop-specific; leafy vegetables such as spinach may be "unsafe," while fruit-type vegetables are considered a safer option. A 2024 study conducted in a moderately Pb-contaminated Nantes garden reinforced this, finding that low-accumulator vegetables like tomato, cabbage, potato, and bean "can all be safely cultivated"(Bouquet et al., 2024). This complex scientific context is strongly reflected in the polarized perceptions of gardeners in Nantes Nord regarding the localized risks and EDS of soil pollution (as detailed in Chapter 4).

5.3.2 Indicator selection

Following the establishment of the overarching MESMIS-FWS framework, the next critical step in its operationalization is the selection of strategic indicators. This process moves from the general system definition to the specific, measurable variables that will be used to assess sustainability. The selection of indicators is a

crucial step in the MESMIS cycle, as it determines what is measured and, therefore, what is managed.

A critical methodological innovation of the FWS Sustainability Index is the direct integration of the empirical survey data presented in Chapter 4. Rather than relying exclusively on top-down, expert-assigned parameters, the structural weighting of the index is directly anchored to the social realities of the Nantes Nord gardeners. The ES and EDS identified as paramount by the community (e.g., as the anxiety surrounding water consumption and the strong valuation of ecological stewardship) function as the empirical justification for the distribution of weights across the Food, Water, and Soil axes. This integration ensures that the resulting diagnostic tool remains faithful to the participatory heritage of the MESMIS methodology, evaluating the system based on the specific socio-ecological parameters that govern the local community's lived experience.

To ensure analytical precision, each axis is further subdivided into conceptual 'scopes' that capture distinct facets of sustainability. The choice and definition of these scopes are not arbitrary but are theoretically grounded to reflect the operational realities of the system. For instance, the Soil axis scopes are structured to mirror established ecological pressure-state-response models, evaluating the baseline *Condition* of the asset, the *Degradation* pressures acting upon it, and the *Stewardship* responses employed by gardeners. Similarly, the Water and Food scopes are defined by their functional utilization, separating direct consumption

dynamics from the broader organizational, institutional, and technological environments that govern their management. This scoping architecture allows the framework to systematically categorize indicators before they are aggregated into broader sustainability attributes.

5.3.2.1 Justifications of selected indicators

A robust indicator must measure something that is both biophysically meaningful within the garden ecosystem and socially relevant to the stakeholders who manage and benefit from it. To structure this selection process, we reintroduce the dual analytical lenses developed in Chapter 3: the core biophysical interactions of the soil-plant-water system and the emergent ES and EDS that these interactions generate. The performance of the FWS nexus is most accurately assessed through these qualitative and functional lenses, which evaluate the system's net contribution to human well-being by considering both the benefits it generates and the potential harms it produces. Therefore, the chosen indicators for the FWS Sustainability Index are designed to represent the optimal state or rate of a biophysical process that is known to underpin a key ES or EDS. This approach ensures that the index is not a disconnected list of abstract metrics, but an integrated diagnostic system grounded in both ecological reality and human values. The FWS Sustainability Index is composed of three primary Axes: Food, Water, and Soil. They serve as the main pillars of sustainability for a soil-based UFG. Each axis is further divided into "scopes" that capture different facets of sustainability. The general architecture and structural weighting of these scopes, presented in Table 5.2, were built through a dual-validation process. As detailed subsequently in Table 5.3, this process systematically synthesizes established ecological literature with the empirical social data and perceptual bundles extracted from the Nantes Nord gardeners in Chapter 4. Following this structural

overview and its theoretical justification, the specific, measurable indicators that populate each of the three axes will be presented and evaluated separately in the subsequent subsections.

The foundational logic for dividing these axes into interconnected scopes is directly adapted from the MESMIS-NEXUS framework (Viana et al., 2023), the theoretical and structural architecture of which is comprehensively described in Section 5.2 of this manuscript, withtin section 5.2.1 (Methodological Heritage from MESMIS) and 5.2.3 (MESMIS-FWS Framework Adaptation). .

Table 5.2. Index system for evaluating FWS sustainability

	Scope	Weight
Soil	Condition	40
	Degradation	30
	Stewardship	30
Water	Human Consumption	10
	Production	50
	Conservation	40
Food	Consumption	40
	Organizational and Institutional Environment	25
	Productive and Technological Environment	35

The participatory analysis utilized to define these specific categories and assign their structural weights relied entirely on the empirical ES-EDS assessment detailed in Chapter 4. Specifically, the stakeholder group for this participatory parameterization consisted of the 54 allotment gardeners in Nantes Nord, whose quantified perceptions and valuations of localized ecosystem services and disservices served as the direct material for weight derivation across the Food, Water, and Soil axes

Table 5.3. MESMIS-FWS pillars and their respective weights

Axis	Scope	Weight	Literature-Based Justification	Empirical Justification from Nantes Case Study
Soil	Condition	40	Represents the foundational capital stock. Soil's physical, chemical, and biological properties determine its capacity to function and provide all other services. It is the primary determinant of potential productivity and resilience.	The high value placed on the "Ecological Stewardship" bundle, which statistically grouped **Soil Conservation** and **Biodiversity**, demonstrates that gardeners perceive the intrinsic health of the ecosystem as a core, integrated value.
	Degradation	30	Represents the negative pressures (e.g. erosion, contamination) that directly reduce soil capital. Managing degradation is a primary goal of sustainable land use.	The emergence of a distinct "Pollution" factor, defined by high concern for **Soil Pollution** and **Water Pollution**, validates the need to explicitly assess and weight these degradation pressures.
	Stewardship	30	Represents the positive human interventions (e.g. conservation practices, amendments) that build and maintain soil capital. It reflects the active management required for sustainability.	The near-universal agreement on the importance of **Education** (Median=4, IQR=0.75) reflects a community deeply engaged in learning and applying stewardship practices.

Axis	Scope	Weight	Literature-Based Justification	Empirical Justification from Nantes Case Study
Water	Production	50	Water is the most critical input for biomass production (food). Its availability and efficient use directly govern yield, which is a primary objective of UFGs.	**Water Consumption** was the *only* EDS to receive a median concern level of 4 ("High concern") with a low IQR of 1.00, making it the single most pressing and uniformly shared anxiety among gardeners. This high weight directly reflects this primary stakeholder concern.
	Conservation	40	Reflects the dual importance of on-site water use efficiency (reducing demand on municipal supplies) and the key ecosystem service of stormwater management for urban resilience.	Women placed a significantly higher value on **Water Regulation** (r=0.51, p<.001), indicating that conservation is a key value for a significant portion of the gardening community.
	Human Consumption	10	While important for gardener health, the volume and systemic impact of water for direct human consumption at the garden site are minor compared to the volumes used for production and managed for conservation.	This scope did not emerge as a significant concern or value in the survey data, supporting its lower relative weight compared to production and conservation.
Food	Consumption	40	Addresses the primary provisioning and cultural services of UFGs: providing nutritious food,	**Food Provision** was a top-rated ES with a median of 4 ("Highly important"), confirming

Axis	Scope	Weight	Literature-Based Justification	Empirical Justification from Nantes Case Study
			enhancing food security, and promoting health and well-being.	its central importance to the gardeners' experience.
	Organizational & Institutional Environment	25	Acknowledges that UFGs are socio-ecological systems. Social cohesion, governance, knowledge sharing, and community participation are critical for long-term viability and resilience.	The "Well-being" bundle from the EFA statistically grouped **Social Cohesion** with **Food Provision**, **Mental Health**, and **Physical Health**, proving that gardeners perceive the social infrastructure as an inseparable component of the garden's overall benefit.
	Productive & Technological Environment	35	Encompasses the technical aspects of cultivation (e.g. crop choice, pest management, and diversification) that determine the efficiency and stability of food production.	The equal weighting with the "Organizational" scope reflects the nature of the "Well-being" bundle, where pragmatic production is valued alongside social and health benefits.

5.3.2.2 Soil Axis Indicator

In the integrative perspective of the MESMIS-FWS model, soil is positioned as the foundational axis. The Soil Axis evaluates the condition of the soil as a capital asset, the pressures leading to its degradation, and the stewardship practices employed to maintain its health. The indicators selected for this axis directly measure the soil properties that govern its capacity to function. Table 5.4 represents the over-weighting of the soil axis.

Table 5.4. Scope of indicators in the Soil axis

	Scope	**Weight**
Soil	Condition	40
	Degradation	30
	Stewardship	30

The weight attributed to each scope (40 for Condition, 30 for Degradation, and 30 for Stewardship, Table 5.3) mirrors established ecological pressure-state-response models. The "Condition" indicators measure the state of the ecosystem asset. The "Degradation" indicators measure the negative pressures acting upon it, while the "Stewardship" indicators measure the positive management responses. While soil condition is directly linked to the quality and quantity of food production, as well as water use efficiency, it is also tied to the degradation and stewardship (chapter

3). Therefore, soil condition has a slightly higher weight than degradation and stewardship. A low score in "Condition" is the symptom; the scores in "Degradation" and "Stewardship" provide the diagnosis, suggesting the appropriate management intervention. The selection of soil functions, their structural weights, and the specific grading thresholds and values presented in the subsequent tables were derived from the expert operationalization of the research team, systematically synthesized with the established agronomic parameters of Barzman *et al.* (2015), Séré *et al.* (2024), and Tripathi *et al.* (2020).

Under the scope of **condition** (Table 5.5), indicators that are direct measures of the soil's physical and chemical state, which were identified in Chapter 3 and cross-referred with Séré *et al.* (2024), were selected. For example, low bulk density and high organic carbon are directly linked to soil structure, which indicates the soil's ability to provide the regulating service of stormwater infiltration (an ES) and resist compaction (avoiding an EDS). All variables for physical and chemical properties were assigned equal weight due to their intrinsic relationship with soil functions in generating food and supporting the water cycle. They are common variables that are often involved in the assessment of soil health, frequently measured, and usually required by Nantes Metropole before establishing a new allotment garden. *Trace elements* directly assess the health-related disservice of soil contamination, a key concern in urban agriculture in Nantes. *Earthworm* was assigned a higher

value due to its being a representation of soil biological activity, an important indicator that supports a resilient and healthy soil.

Table 5.5. Indicators of the soil condition scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
Condition	40	Physical properties	12	Top-soil depth (cm)	Ordinal	3	>100
						2	50-100
						1	25-50
						0	<25
				Texture class	Ordinal	3	Balanced
						2	Loamy
						1	Clayey
						0	Sandy
				Bulk density (g cm^{-3})	Ordinal	3	0.8-1.2
						2	1.2-1.5

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
						1	1.5-1.7
						0	<0.8 or >1.7
				Slope (%)	Ordinal	3	0-2
						2	2-5
						1	5-15
						0	>15
		Chemical properties	18	Electrical conductivity ($\mu S\ cm^{-1}$)	Ordinal	3	<500
						2	500-1000
						1	1000-2000
						0	>2000
				Total organic carbon	Ordinal	3	>5.8

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
				(g/kg^{-1})		2	3.5-5.8
						1	1.2-3.5
						0	<1.5
				Total Nitrogen (g/kg^{-1})	Ordinal	3	10-20
						2	>20
						1	2-10
						0	<2
				Total phosphorus (g/kg^{-1})	Ordinal	3	0.06-0.1
						2	>0.1
						1	0.04-0.06
						0	<0.04

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
				Trace elements (mg kg^{-1})	Ordinal	3	<NPGB
						2	NPGB-2xNPGB
						1	2xNPGB-10NPGB
						0	>10xNPGB
		Biological property	10	Earthworm	Ordinal	10	>300
						5	150-300
						3	50-150
						0	<25

The **degradation** scope is designed to assess the active pressures and vulnerabilities that threaten the soil's functional capacity, rather than just its static condition. The weights were distributed according to the relevance of indicators from previous analysis. A weight of 10 was assigned equally to “Synthetic input”, “Evidence of erosive”, and “Extreme weather” due to their equal importance in affecting the quality of soil. Table 5.6 explains the details of this scope.

The inclusion of the "Synthetic input" indicator, which measures the reliance on synthetic pesticides and inorganic fertilizers, is central to this logic. From the study perspective, this indicator functions as a primary proxy for chemical degradation pressure. While these inputs are typically applied to maximize the *Productivity* attribute of the Food axis, they can introduce a critical trade-off, potentially undermining the system's long-term *Stability*. Within the Soil axis, these inputs can degrade soil biological properties and negatively alter soil chemistry. Therefore, higher scores were given to practices that do not trigger long-term effects on soil, such as the use of preventative practices in managing pests or the use of organic fertilizer.

Table 5.6. Indicators of the soil degradation scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
Degradation	30	Synthetic input	10	Integrated pest management	Ordinal	5	Preventative practices only
						3	Physical/mechanical control
						1	Biological/Biochemical
						0	Board-spectrum synthetic pesticides c
				Fertilizer input	Ordinal	5	Organic fertilizers
						3	A combination of organic and inorganic fertilizers
						1	Slow delivery of synthetic fertilizers (solid)
						0	Rapid delivery of synthetic fertilizers (liquid)
			10	Wind erosion	Nominal	5	No

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
		Evidence of the erosive process				0	Yes
				Water erosion (diffuse/concentrated)	Nominal	5	No
						0	Yes
		Extreme weather conditions	10	Heavy rain	Nominal	5	Occasional
						0	Seasonal
				Flooding	Nominal	5	No
						0	Yes

The "Evidence of the erosive process" indicator, which directly monitors for visible wind and water erosion, was added to capture the physical dimension of soil degradation. This indicator is fundamentally a nexus measure, as water erosion represents the direct, destructive interaction of the Water axis (in the form of surface runoff) on the Soil axis. The degradation is twofold: it signifies a direct loss of the soil asset itself, compromising the properties measured in the "Condition" scope, including "Topsoil depth" and "Total organic carbon", and affects food production and water retention.

The **stewardship** scope in the FWS framework (Table 5.7) is structured to evaluate the active management interventions applied to the system. The "Preservation practices" indicator specifically quantifies key agricultural techniques, bundling variables such as "Disturbance minimization (tilling)," "Cover crop/mulching," and "Crop rotation". These practices were identified in Chapter 3 as essential for breaking the negative feedback loops of urban soil degradation. They are also tangible mechanisms that directly address the MESMIS attribute of Stability, which is defined as the conservation of the resource base. They were assigned an equal weight due to their similar intrinsic values.

The "Institutional support" indicator is included to reflect the socio-political context, as the MESMIS framework is designed to evaluate management systems in their entirety. The inclusion of "Soil pollution intervention" is essential to assess whether and how gardeners are actively managing the presence of trace metal

elements. The modest weight of 5 reflects that this is a specific, targeted intervention in response to a particular problem, rather than a universal set of daily management practices. Active interventions with instruction from the city municipality, which can include remediation or adaptive practices, including selecting low-accumulator crops or constructing raised beds. There are stewardship actions to protect the "Food Provision" service.

Table 5.7. Indicators of the soil stewardship scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
Stewardship	30	Preservation practices	20	Disturbance minimization	Ordinal	5	No tilling
						2.5	1-3 times
						0	4 or more
				Cover crop/ Munching	Nominal	5	Yes
						0	No
				Crop rotation	Nominal	5	Yes
						0	No
				Vegetation cover %	Ordinal	5	75%
						2.5	50 – 75 %
						0	<50%
		Institutional supports	10	Soil pollution intervention	Nominal	5	Regulated
						0	Non existent
					Nominal	5	Yes

				Public participation		0	No

5.3.2.3 Water Axis Indicators

The allocation of weights within the Water axis (Human Consumption 10, Production 50, and Conservation/Degradation 40) is a direct adaptation of the MESMIS-NEXUS framework to the specific context of the Nantes Nord allotment gardens. The original MESMIS methodology utilized a triad of social, economic, and agroecological dimensions. The NEXUS-Pampa adaptation (Viana et al., 2023), which informs the FWS framework, reformulates these into the Water-Energy-Food (WEF) nexus. Within this logic, the Water axis is not a single entity but is disaggregated into scopes that reflect its distinct roles: its function for direct human needs, its role as a productive input, and its potential as a source of system degradation (or the corresponding need for conservation). Table 5.8 presents the overall weightings of the water axis.

Table 5.8. Scope of indicators in the Water axis

	Scope	**Weight**
Water	Human consumption	10
	Production	50
	Conservation	40

The high, interconnected weightings for "**Production**" (50) and "**Conservation**" (40) capture the central water-related tension in the Nantes Nord garden system. The "Production" scope, which addresses water availability and use efficiency for crops, is assigned the highest weight (50) because it aligns directly with the system's primary purpose: food provision. It is also related to the single greatest concern perceived by the gardeners: "Water Consumption" for irrigation during the growing season. "**Conservation**" scope total weight was set at 40, which includes conservation practices, as it is critical for evaluating the system's Stability and Resilience—two core attributes of the MESMIS framework. Therefore, the 50/40 split reflects the interconnected logic presented in the NEXUS-Pampa framework, which states that "water dynamics directly connect production and degradation". However, specific variables and their weights were tailored to prioritize the production concerns and water conservation specific to Nantes Nord.

The relatively low weighting of 10 for the "**Human Consumption**" scope reflects the specific realities of the necessity of water for human use in gardens (Table 5.9). This scope assesses the quality and quantity of water for direct human use, such as drinking and sanitation, for gardeners while working in urban gardens. In the context of Nantes, access to potable water is not a primary limiting factor for the gardeners. This rationale is mirrored in the NEXUS-Pampa study , which notes that while "undoubtedly important," water for human consumption may not be a

"limiting factor" in urban areas, thus justifying a lower relative weight compared to more pressing issues.

Table 5.9. Indicators of the water for human consumption scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
Human consumption	10	Water quantity	5	Source meets consumption	Ordinal	5	total sources
						4	total sources
						3	total sources
						2	total sources
						1	total sources
						0	No access
		Water quality	5	Quality	Ordinal	5	Good
						2.5	Average
						0	Bad

The **production** scope of the Water axis (Table 5.10), which in the FWS framework has a total weight of 50, is subdivided into three key indicators: " Irrigation Water," "Water-use efficiency," and "Susceptibility to drought," with weights of 10, 30, and 10, respectively. This weighting structure is adapted from the MESMIS-NEXUS framework to reflect the specific environmental and social context of Nantes Nord. The " Irrigation Water" indicator, weighted at 10, assesses the basic availability of water for agricultural production, such as meeting the physiological

demands of plants and watering animals. Its relatively low weight is appropriate for the Nantes context. As the main sources of irrigation water come from rainwater harvesting and tap water, the water source and its quality are a necessary baseline, but are not considered the primary limiting factor for sustainability.

Table 5.10. Indicators of the water production scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
Production	50	Irrigation water source	10	Source meets consumption	Scalar	10	total (scale 5)
						8	total (scale 4)
						6	total (scale 3)
						4	total (scale 2)
						2	total (scale 1)
						0	No network
		Water-use efficiency	30	Cultivation system	Ordinal	30	Permaculture /biological system
						20	Intensive system
						10	Conventional system
		Susceptibility to drought	10	Occurrence	Nominal	5	No
						0	Yes
				Frequency	Ordinal	5	Occasionally

						0	Annually

The "Water-use efficiency" indicator (Table 5.10) is assigned the highest weight of 30, making it the central component of this scope. This indicator measures the efficiency with which the cropping systems utilize the available water, which is closely linked to soil quality, irrigation methods, and crop selection. Water use efficiency based on the cultivation systems is well-established in agricultural studies. This high weighting is directly justified by the specific critical points of the Nantes Nord system. First, it aligns with the highest concern identified among the gardeners themselves, who rated "Water Consumption" as their top disservice. Second, it reflects the region's climatic reality of relatively dry summers, with July being the driest month, which coincides with the peak growing season. Third, it addresses the top-down pressure from France's national "Plan Eau 2023-2030," which mandates a 10% reduction in water abstraction. This indicator thus evaluates the system's productivity and its adaptability by measuring the active management response to perceived, climatic, and policy-driven water scarcity.

The "Susceptibility to summer drought" indicator is given a weight of 10. This indicator evaluates the system's vulnerability to acute, periodic climatic shocks, rather than its day-to-day operational efficiency. It is a key measure of the MESMIS attributes of Resilience and Reliability—the system's capacity to withstand and recover from disturbances. While Nantes is not an arid region, its dry summers represent a recurring risk, and climate change is expected to increase the

frequency of such extreme events. The NEXUS-Pampa framework justifies this weighting by noting that although drought may not occur every year, its impact is significant when it does. The 10-point weight in the Nantes model, therefore, acknowledges this specific climatic risk without overstating it, balancing it against the more immediate and manageable issue of "Water-use efficiency," which serves as the primary management strategy to mitigate this susceptibility.

Table 5.11. Indicators of the water conservation scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
Conservation	40	Plant management	10	Origin of vegetables	Ordinal	10	Native
						5	Mixed
						0	Non-native
		Water management	10	Irrigation system	Ordinal	10	Buried
						7.5	Drip
						5	Bucket
						2.5	Hose
		Soil compaction management	10	Decompaction methods	Ordinal	10	>2
						5	1-2
						0	0
		Water reuse/recycle	10	Collection pathways	Ordinal	10	>2
						5	1-2

						0	0

Lastly, the **conservation** scope of the Water axis, which holds a significant weight of 40, was designed to evaluate the active management practices that mitigate water-related degradation and enhance resource preservation (Table 5.11). This scope is conceptually analogous to the "Degradation" scope in the MESMIS-NEXUS framework, which includes the "existence of conservationist practices" as its most heavily weighted component. The high overall weight (40) is justified by its direct relationship to the "Production" scope; in the nexus logic, efficient production is inseparable from managing degradation. The decision to assign an equal weight of 10 to all four indicators (i.e. "Plant management," "Water management," "Soil management," and "Water reuse/recycle") stems from a systemic understanding that these practices are complementary and equally critical, rather than hierarchical. This approach aligns with the principles of conservation agriculture, which posits that soil, plant, and water (runoff) management practices must be implemented as an integrated set to be effective. The MESMIS-NEUS framework, for example, groups "Soil Management," "Plant Management," and "Water Management" (field/runoff management) as distinct but complementary practices necessary for erosion control. An equal weighting reflects the theoretical assumption that a failure in one area (e.g. lack of soil compact management) cannot be fully compensated by excellence in another (e.g. planting of native plants), as they address different aspects of the same degradation process.

Individually, each indicator addresses a specific aspect of the system's sustainability. "Soil compact management" (e.g. "no-till method") and "Plant management" (e.g. "native plant") are the primary strategies to protect the soil surface, build organic matter, and maximize water-use efficiency and infiltration, directly enhancing the system's Stability against "Water erosion". The inclusion of "Water reuse/recycle" with an equal weight reflects the system's Adaptability, ensuring its viability in the face of both climatic and policy-driven water scarcity.

5.3.2.4 Food Axis Indicator

The division of the Food axis within the FWS framework is structured into three distinct scopes: "Consumption" (weighted at 40), "Organizational and Institutional Environment" (25), and "Productive and Technological Environment" (35). The categories and weights are methodological decisions rooted in the MESMIS-NEXUS framework. This structure was derived from a participatory analysis (MESMIS Stage 3) of the system's "strengths and weaknesses". This three-part design is necessary to capture the complete function of the allotment gardens in Nantes Nord. It assesses (1) the enabling social and policy context, (2) the on-the-ground management practices, and (3) the ultimate social and nutritional purpose of the food produced. This is particularly relevant in the Nantes context, where allotment gardens are not just agricultural plots but are formally integrated into urban renewal strategies. Table 5.12 presents the overall weightings of the food axis. Food Axis represents the productive outputs of the garden, its role in

community well-being, and the institutional and technological environments that govern it.

Table 5.12. Scope of indicators in the Food axis

	Scope	Weight
Food	Consumption	40
	Organizational and Institutional Environment	25
	Productive and technological Environment	35

The weighting within the "**Consumption**" scope of the Food axis, which is the most heavily weighted scope at 40 points, is distributed among "Self-consumption" (20), "Close network sharing" (10), and "Social sharing" (10). This 20/10/10 split is a deliberate allocation tailored to the specific socio-economic context of the allotment gardens (Table 5.13). The highest weight (20) is assigned to "Self-consumption," as this indicator measures the system's most direct and fundamental contribution to the gardener's household. This prioritization aligns with the primary motivation of "Food Provision" identified in surveys of Nantes Nord gardeners, which is a core component of their "Well-being" bundle. The capacity of a garden to directly improve household food security and access to fresh produce is its primary sustainability function. This focus on self-provisioning is consistent with the MESMIS attribute of Productivity at the household level, as well as the "Consumption of Own Production" indicator found in the MESMIS-NEXUS framework.

The "Close network sharing" indicator (weight 10) expands the assessment from the individual household to the immediate community, quantifying the garden's role in building informal social capital.

Table 5.13. Indicators of the food consumption scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
Consumption	40	Self-consumption	20	Portion of vegetables covered by products from the gardens	Ordinal	20	>75%
						15	50-75%
						10	25-50%
						5	10-25%
		Close network sharing	10	Sharing with neighbours/ friends/	Ordinal	10	Frequently
						5	Sometime
						0	Never
		Social sharing	10	Sharing with the public (school/food bank)	Ordinal	10	Frequently
						5	Sometime
						0	Never

This is a critical function in Nantes Nord, a district historically characterized by physical fragmentation and social housing "archipelagos" that urban renewal projects like the Projet Global Nantes Nord specifically aim to address by fostering "social cohesion". This indicator directly measures one of the mechanisms for achieving the "Social Cohesion" that gardeners themselves perceive as a highly important benefit. The sharing of produce with friends and neighbors is a well-

documented social service of urban gardening that reinforces interpersonal relationships and helps transform urban spaces into social hubs.

Finally, the "Social sharing" indicator (weight 10) is weighted equally to "Close network sharing" but captures a different, more formal dimension of distribution that aligns with the MESMIS attribute of Equity—the fair distribution of benefits. In Nantes, the municipality's official garden policy explicitly defines and supports gardens to distribute fresh, locally grown vegetables to benefit its citizens, often via local associations and food banks. Therefore, the 20/10/10 weighting scheme creates a balanced evaluation: half of the scope's value (20) focuses on the system's primary role in addressing the gardener's own food security (Self-consumption), while the other half assesses its vital secondary function of building community and addressing broader social equity, both informally (sharing with close network) and formally (sharing with local communities, such as school or food bank), which are central goals of the urban regeneration strategy for Nantes Nord.

Organizational and institutional environment scope (as shown in Table 5.14), which accounts for 25 points of the Food axis, is designed to evaluate the socio-political and structural framework that governs the allotment garden system. This approach is consistent with the MESMIS methodology and mainly derived from the MESMIS-NEXUS Food axis, where irrelevant indicators were removed (e.g. those that were primarily associated with market conditions. It mandates an

evaluation of the entire management system, including its social and institutional components, rather than just its productive output.

Table 5.14. Indicators of food organizational and institutional environment scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grading	Grading value
Organizational and Institutional Environment	25	Social and associative participation	5	Degree of participation in the garden association and local community	Ordinal	5	Highly participated
						3	Average
						1	Low
						0	Never
		Support organizations	5	Degree of relationship with support organizations	Ordinal	5	Frequently
						3	Occasionally
						1	Rarely
						0	Never
		Traditional and culture	5	The importance of culture and tradition in the activity	Ordinal	5	High
						3	Moderate
						1	Little
						0	Nothing important
		Public policies	5	Supporting local policies and government	Nominal	5	Exist
						0	Non-existent/ Unclear
			5		Ordinal	5	Good

		Logistics and infrastructure		Condition of equipment and infrastructures		3	Regular
						1	Bad
						0	Non-existent

The decision to assign an equal weight of 5 points to all five indicators is a methodological choice that reframes the logic of this scope. Rather than prioritizing one element over others, this equal weighting posits that these five components are an interdependent and equally critical set of pillars. This balanced assessment is justified by the specific context of UFGs in Nantes. "Public policy" (5) is a foundational pillar, representing the formal municipal framework in securing land, supporting agriculture organizations, or testing water and soil quality for agriculture. However, this policy is just as important as "Logistics and infrastructure" (5), which measures the tangible, material support from the city, such as the water tank, equipment, and site preparation necessary for gardening to be viable. Similarly, "Social and associative participation" (5) is equally essential, as it assesses the activation of these spaces, where the majority of gardeners socialize and learning. This indicator measures the UFG system's success in fulfilling its core social mandate.

The remaining two indicators are equally vital for the system's resilience. "Support organizations" (5) accounts for the crucial role of external partners. Urban allotments often involve a network of non-profits and research institutes. In the case of Nantes, notable institutions and organizations such as IRSTV, ECOS, and

MAAD provide essential expertise and facilitation. Finally, "Tradition and culture" (5) measures the system's internal social cohesion and cultural embeddedness, functioning as a foundational component for the Equity attribute. This reflects the strong, shared "gardening culture" and knowledge transfer observed among the gardeners, which ensures the system's long-term viability beyond the lifespan of any single project or policy. By weighting all five pillars equally, the framework asserts that formal policy, physical infrastructure, social activation, external support, and cultural embeddedness are all essential for the system's success.

Lastly, in the FWS framework, the **productive and technological environment** scope is assigned 35 points (Table 5.15), making it a critical component of the Food axis. This scope evaluates the "inside the garden" aspects of the system, focusing on the tangible resources, tools, and on-the-ground management practices that gardeners employ. Its high weighting is justified as it directly measures the system's core MESMIS attributes of Productivity (efficiency of management) and Self-reliance (dependence on inputs). In the Nantes context, this scope is essential for connecting institutional goals with the observable practices of the gardeners.

The weighting within this scope is differentiated to prioritize the two most fundamental inputs for production: human capital and land security. "Labour availability" (10 points) is the most heavily weighted human input, measured by the time gardeners visit their plots. Data from Nantes Nord shows that gardeners are predominantly older adults (85% over 55) who invest significant and regular

time in their plots (most visit 3-5 days a week or more). This intense labour is the primary driver of Productivity in this non-mechanized system and is a key mechanism for delivering the "Well-being" benefits (physical and mental health) that gardeners value so highly. "Land tenure policy/Ownership" (10 points) is the corresponding foundational input, measuring if the garden is regulated by law. Its equal high weight is justified by extensive research identifying insecure land tenure as one of the greatest barriers to sustainable urban agriculture. When tenure is insecure, gardeners are less likely to invest in long-term stewardship, such as building soil health or planting perennials, making it a cornerstone of the attribute Stability.

Table 5.15. Indicators of food productivity and technological environment scope

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grad-ing	Grading value
Productive and Technological Environment	35	Garden management	5	Use of crop management tools	Nominal	5	Yes
						0	No
		Dependence on economic input	5	Degree of economic concern	Scalar	5	No concern
						2.5	Moderate
						0	High
		Labour availability	10	Time availability	Scalar	5	Every day
						2.5	Few times a week

Scope	Weight	Indicator	Sub-Weight	Variable	Data type	Grad-ing	Grading value
						0	Less than once a week
		Land tenure policy	10	Ownership regulated by law	Nominal	10	Regulated
						0	Not regulated
		Biodiversity enhancement	5	Biodiversity protection pathways	Scalar	5	> 2
						2.5	1-2
						0	Non-existent

The remaining 15 points are distributed equally among three indicators (5 points each) that measure the quality and style of management. "Garden management tool" (5 points), which assesses the use of planning tools like calendars or books, serves as a proxy for the system's Adaptability. It measures the level of applied knowledge and forward planning, which indicates a capacity to learn and optimize. "Dependence on economic input" (5 points), measured by the gardener's level of economic concern, is a direct assessment of Self-reliance. A system with low dependence on costly external inputs is more resilient and, critically, more accessible to residents with high rates of poverty. Finally, "Biodiversity enhancement" (5 points) directly links the Food axis to ecological goals. This indicator is essential given that enhancing biodiversity is an explicit objective of NbS. Its inclusion is further validated by survey data showing that Nantes Nord gardeners perceive "Biodiversity" as a "Highly important" ecosystem service.

5.3.3 Adapting FWS indicators for MESMIS Sustainability Properties

5.3.3.1 Productivity

MESMIS provides a robust, systemic, and participatory methodology for assessing sustainability. Its core strength lies in moving beyond simple checklists to evaluate systems based on a set of fundamental, dynamic properties. While the original framework proposed seven attributes, subsequent methodological refinements and applications often grouped these into five core properties: Productivity; Stability (encompassing Reliability and Resilience); Adaptability; Equity; and Self-management (or Self-reliance).

In the MESMIS context, *Productivity* is defined as the system's capacity to produce a specific, desired combination of goods and services at a given point in time. This property encompasses the system's overall "efficacy or efficiency" in generating its intended outputs. Viana *et al.* (2023) operationalize *Productivity* in a sophisticated, process-oriented manner. Their allocation for this attribute includes not only the final outputs ("Market structure") but also the critical inputs ("Water for Production," "Fossil fuel") and the efficiencies ("Water use efficiency") that govern the productive process. For the FWS framework, which evaluates UFGs, this logic implies that *Productivity* must capture the full spectrum of functions. This includes the primary biophysical provisioning service (food) as well as the cultural

services (e.g. sharing) that are a key objective of these systems. Furthermore, it must account for the efficiency of the core inputs, namely water and human labour, that make this generation possible. Given that Nantes gardeners identify summer water availability as a primary concern, the indicators Irrigation Water (Source meets consumption) and Water-use efficiency (Cultivation system) are essential measures of productive potential and efficiency

The specific selection of indicators aggregated in Table 5.16 to measure systemic Productivity is theoretically anchored in the preceding chapters. As conceptualized in Chapter 3, the primary ES of UFGs extend beyond mere biomass extraction to include the active co-production of social capital. This is empirically validated by the Nantes Nord case study in Chapter 4, which demonstrated that gardeners perceive food provision, dedicated labor, and close network sharing as intertwined components of their overarching well-being. Consequently, the following table synthesizes both the biophysical efficiencies (e.g., water-use) and the socio-technical practices (e.g., labor availability, sharing networks) required to generate the system's intended outputs to generate the system's intended holistic outputs (as summarized in Table 5.16).

Table 5.16. FWS Nexus indicators that compose the production attribute

Nexus	Indicator	Weight

Food	Self-consumption	20
	Close network sharing	10
	Social sharing	10
	Labour availability	10
	Garden management tool	5
Water	Irrigation Water	10
	Water-use efficiency	30

5.3.3.2 Stability

Stability, Reliability, and Resilience in the MESMIS-NEXUS were comprised into the *Stability*, arguably the most complex property. It represents the system's ability to maintain its function and integrity over time and in the face of disturbances. They are deconstructed below:

- *Stability*: This is the foundational concept, defined as the system's "capability to reproduce those processes needed to attain productivity" and, most critically, the "conservation of the resource base". It is the

system's ability to "produce the desired goods and services without degrading its existing resources"

- *Reliability*: This property describes the system's response to normal variability. It is the "capacity of the system to maintain its productive and stable state of equilibrium when facing 'normal' variations" in its environment, such as seasonal weather fluctuations.

- *Resilience*: This property describes the system's response to extreme events. It is defined as the "degree to and rate at which a system, after 'shock' or 'stress', is able to again produce the necessary goods and services" and return to its equilibrium state.

The FWS framework's central thesis, that soil is the foundational living infrastructure and primary capital asset, provides a powerful and elegant justification for grouping these three attributes. In this context, the MESMIS definition of *Stability*, defined as conservation of the resource base (Viana et al., 2023), maps directly onto the biophysical state of the soil capital asset. A healthy, high-quality soil asset is a stable system. This stable state is precisely what confers *Reliability* and *Resilience.* Therefore, this Stability property is best operationalized by allocating indicators that measure: (1) the biophysical state of the soil asset (*Stability*) - Physical Properties, Chemical Properties, and Biological Properties, and (2) the system's inherent response to perturbations

and shocks (*Reliability* and *Resilience*) - Evidence of the erosive process, Extreme weather conditions, and Susceptibility to drought. Vegetation cover (%) is included as a direct measure of the soil's protected state, which confers both resilience to raindrop impact and reliability against evaporation (detailed in Table 5.17).

Table 5.17. FWS Nexus indicators that compose the stability attribute

Nexus	**Indicator**	**Weight**
Soil	Physical Properties	12
	Chemical Properties	18
	Biological Properties	10
	Evidence of the erosive process	10
	Extreme weather conditions	10
	Vegetation cover (%)	5
Water	Susceptibility to drought	10

5.3.3.3 Adaptability

A distinction must be made between the *Stability* property and *Adaptability*. While *Stability* describes the system's inherent dynamic state, *Adaptability* is a measure of the human capacity to manage that system. It is defined as the "capability of the system to continue producing goods and services when facing long-term or permanent changes". This is achieved by "accommodating innovation in an evolving learning process" and finding new states of equilibrium. The "Nexus Pampa" precedent (Viana et al., 2023) makes this distinction clear. The study allocates indicators of proactive human action, innovation, and social capital to *Adaptability*, including the "existence of conservationist practices," "productive diversification," "support organizations," and "succession/ transmissibility". This logic separates the state (e.g. "drought susceptibility," which was placed in *Stability*) from the human actions taken to address that state (e.g. "conservationist practices," which were placed in *Adaptability*). For the FWS framework, this means that Adaptability is the property that captures active stewardship. It is not the result (e.g. a high soil carbon level) but the process (e.g. the practice of cover cropping) that a gardener employs to achieve that result (see Table 5.18).

Table 5.18. FWS Nexus indicators that compose the adaptability attribute

Nexus	**Indicator**	**Weight**
Soil	Disturbance minimization	5

Nexus	Indicator	Weight
	Cover crop/munching	5
	Crop rotation	5
Water	Plant management	10
	Water management	10
	Soil management	10
	Water reuse/recycle	10
Food	Biodiversity enhancement	5
	Logistics and infrastructure	5

5.3.3.4 Equity

Equity is a social property, defined as the system's "ability to distribute all costs and benefits fairly between its stakeholders". Viana *et al.* (2023) map indicators here that measure the distribution of benefits (e.g. "self-consumption and direct sale") and the distribution of power ("social and associative participation"). For the FWS framework, this property must capture the distribution of both benefits (food, community well-being) and costs. In

the context of urban agriculture, a primary "cost" is not just economic, but is the potential for exposure to risk. The case study context in Nantes specifically identifies soil contamination with "trace metal elements, particularly Pb and As," as a primary concern, noting the presence of lead. This belongs to the environmental justice and public health issue. A gardener working on a contaminated plot bears a possible inequitable health cost. Thus, indicators of contamination should belong to *Equity* (Table 5.19).

Table 5.19. FWS Nexus indicators that compose the equity attribute

Nexus	**Indicator**	**Weight**
Soil	Trace elements	3
	Public participation	5
Food	Tradition and culture	5
	Social and associative participation	5
	Close network sharing	10
	Social sharing	10

5.3.3.5 Self-Management

Finally, s*elf-management* is defined as the "capability of a system to regulate and control interactions with outlying systems" and promote an "acceptable level of self-reliance (self-empowerment)". It is a measure of the system's autonomy and its level of dependence on external forces. For the FWS framework, this property aims at indicators that measure dependence on external resources (e.g. synthetic fertilizers, pesticides, economic inputs). However, the definition also includes "self-empowerment". This implies a more nuanced understanding than simple isolation. Autonomy is also enhanced by factors that empower the gardener to act, such as secure land tenure, strong social networks, and supportive institutional policies. A gardener with secure tenure is empowered to make long-term, autonomous decisions in a way a gardener with precarious tenure is not. See table 5.20 below for more details.

Table 5.20. FWS Nexus indicators that compose the self-management attribute

Nexus	**Indicator**	**Weight**
Soil	Synthetic input	10
	Soil pollution intervention	5

Nexus	Indicator	Weight
Food	Dependence on economic input	5
	Land tenure policy/Ownership	10
	Support organizations	5
	Public policy	5

5.3.4 Normalization of the sustainability attributes

There is a discrepancy in weighting between the MESMIS-FWS framework and the MESMIS-WEF framework presented by Viana *et al.* (2023). Conversely, the WEF-MESMIS framework begins with the premise that all five sustainability attributes are equally significant, defining each as a standardized 100-point scale. This is quantitatively confirmed by summing the indicator weights within each of their attribute tables (e.g. Adaptability, Self-management, Equity, Stability, and Productivity all have indicator weights that sum to 100). The 37 WEF indicators are then selected, weighted, and distributed within these five pre-defined 100-point properties, often with a single indicator's weight being split across multiple attributes. This design is optimized for standardized performance comparison, allowing researchers to state. For example, the system is performing better on Self-management (72.31) than on Equity (62.75).

In the MESMIS-FWS model, the weighting is established at the indicator level, grounded in the specific biophysical realities and identified critical points of the Nantes UFG system. These pre-weighted indicators are then allocated to the five MESMIS sustainability attributes (Productivity, Stability, Adaptability, Equity, Self-management). Consequently, the total maximum score for each attribute is not a predefined value, but rather the sum of the indicators allocated to it. This results in the diagnostically significant, unequal attribute totals (e.g. maximum scores of Productivity 95, Stability 75, Equity 38), which serve as a key finding that quantifies the relative systemic importance of each attribute within the specific Nantes context. Table 5.21 provides a synthesis of this aggregation, illustrating the maximum possible score for each attribute prior to normalization.

Table 5.21. Maximum possible scores of the MESMIS-FWS Sustainability Attributes

MESMIS Attribute	Total
Productivity	95
Stability	75
Adaptability	65
Equity	38
Self-Management	40

To reconcile the FWS-MESMIS framework's diagnostically unequal attribute totals for visualization purposes (e.g., in a radar diagram), a normalization process was carried out. Normalization converts these disparate raw scores onto a standard 0-100 scale, reflecting the percentage of performance achieved for each attribute, thereby allowing for comparison. Assuming the minimum score is 0, the min-max normalization is simplified and defined by the following formula

$$Score_{Normalized} = \left(\frac{Score_{Observed}}{Score_{Maximum}}\right) \times 100$$

$Score_{Observed}$ is the raw score achieved by a garden for a specific attribute, calculated by summing the graded scores of its constituent indicators

$Score_{Maximum}$ is the unique maximum total score of each attribute

5.3.5 Data collection and processing

The data corpus underpinning the MESMIS-FWS framework analysis was developed via semi-structured interviews. We operationalized the data collection using an instrument derived from the foundational MESMIS methodology, which was augmented with supplementary inquiries informed by prior urban garden research undertaken at IRSTV. The instrument design was iterative, commencing with pilot interviews conducted with association board members of the AC garden.

This piloting phase served to refine the instrument's structure, question phrasing, and the logical flow of information. The finalized questionnaire protocol, comprising 43 questions, is detailed in Appendix 4. Interviews were administered in French by a two-person research team, a structure intended to enhance procedural rigor and data capture. The mean duration for completing the instrument was approximately 1.5 hours per interview. Subject to participant consent, all interviews were audio-recorded. Subsequent transcription and translation (French to English) were performed by an IRSTV intern and a volunteer. I subsequently undertook the analytical coding, transforming the qualitative and quantitative responses into weighted variables appropriate for the MESMIS framework. To analyze the resulting dataset, we employed non-parametric statistical methods similar to those in the previous chapter, executed in R (R Core Team, 2025). Specifically, the Kruskal-Wallis and Friedman tests were utilized to assess potential differences between the five studied gardens (inter-group) and within individual gardens (intra-group), respectively. Significant findings were further interrogated using Dunn’s post-hoc test for pairwise comparisons.

A significant methodological constraint must be addressed regarding the soil condition indicators. We did not conduct de novo soil sampling or analysis for this study. Instead, I relied on a pre-existing soil database compiled during the antecedent URBiNAT and JASSURE projects, which encompasses the five garden sites. This reliance on secondary data introduced critical challenges. The database possessed limited sampling density within each garden, and, crucially, a spatial

misalignment existed between the plots sampled for the database and the plots associated with our interview participants. Confronted with this data non-correspondence, an average set of weights for soil condition was calculated for each of the five gardens, and this single, averaged value was uniformly assigned to all interviewed plots within that respective garden. This decision constitutes a methodological compromise. By averaging the soil data, we inherently masked intra-garden variability and eliminated any plot-level differentiation for this indicator. This forced homogenization necessarily impacts the granularity of the final calculated sustainability weights, the repercussions of which are explored in the discussion section.

5.4 RESULT AND ANALYSIS

5.4.1 Overall FWS Nexus Performance

The initial phase of the analysis establishes a baseline profile for the entire 54-plot network, representing the "average" state of a UFG plot in Nantes Nord. The mean normalized scores for the three FWS axes, visualized in the network-level radar chart (Figure 5.2), indicate a system that is, on average, strongest in the Soil axis,

with a mean score of 72.26. This is followed by the Food axis (Mean: 57.39) and the Water axis (Mean: 55.76).

At the aggregate level, the sustainability profile suggests a system of apparent

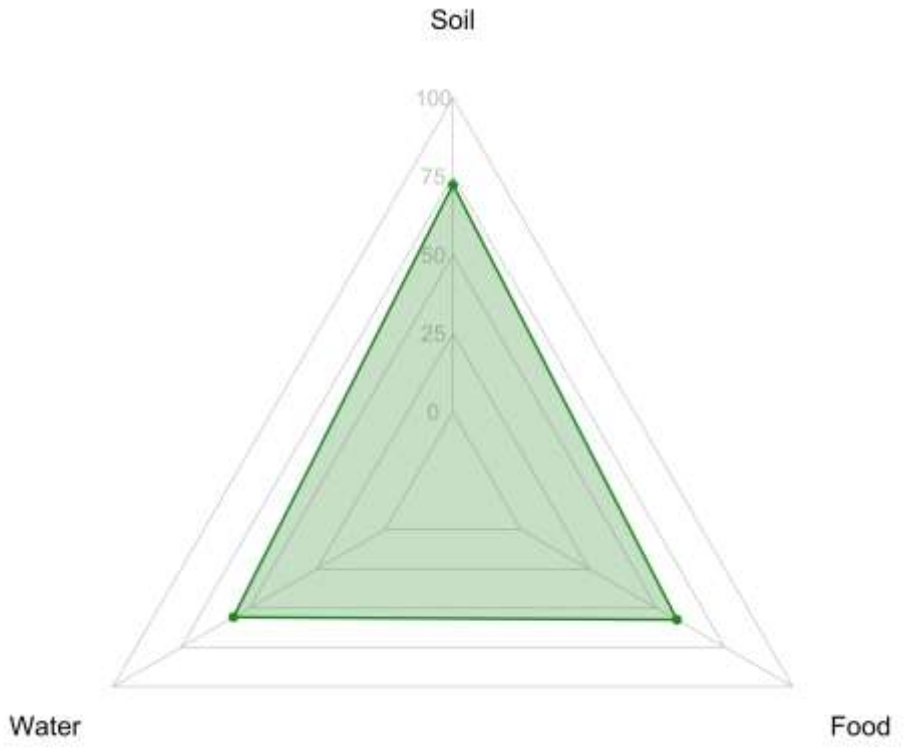

Figure 5.2. Overall performance of UFGs in Nantes Nord

robustness. The 'Soil' component, in particular, registers as a high-performing ecological foundation, aligning with its conceptualization as the system's core capital asset. However, this composite view, while offering a convenient high-level summary, is analytically insufficient and potentially misleading. Such aggregation inherently masks the critical heterogeneities and structural tensions that are diagnostic of system function. A necessary disaggregation, examining the

distributions across the 37 constituent indicators, reveals a significant internal dichotomy. This analysis uncovers opposing patterns: exceptional performance is concentrated in indicators related to established structural and institutional support. Conversely, notable underperformance is evident in indicators contingent upon individual social agency and localized, day-to-day management practices. This polarization points to a potential misalignment between high-level governance frameworks and the realities of on-the-ground implementation.

An examination of the indicator distributions reveals a divergent pattern, as detailed in violin plots on Figure 5.3, Figure 5.4 and Figure 5.5. These Figures display raw, un-normalized scores where the maximum possible value varies by indicator (ranging from 5 to 30). The median scores plotted represent the

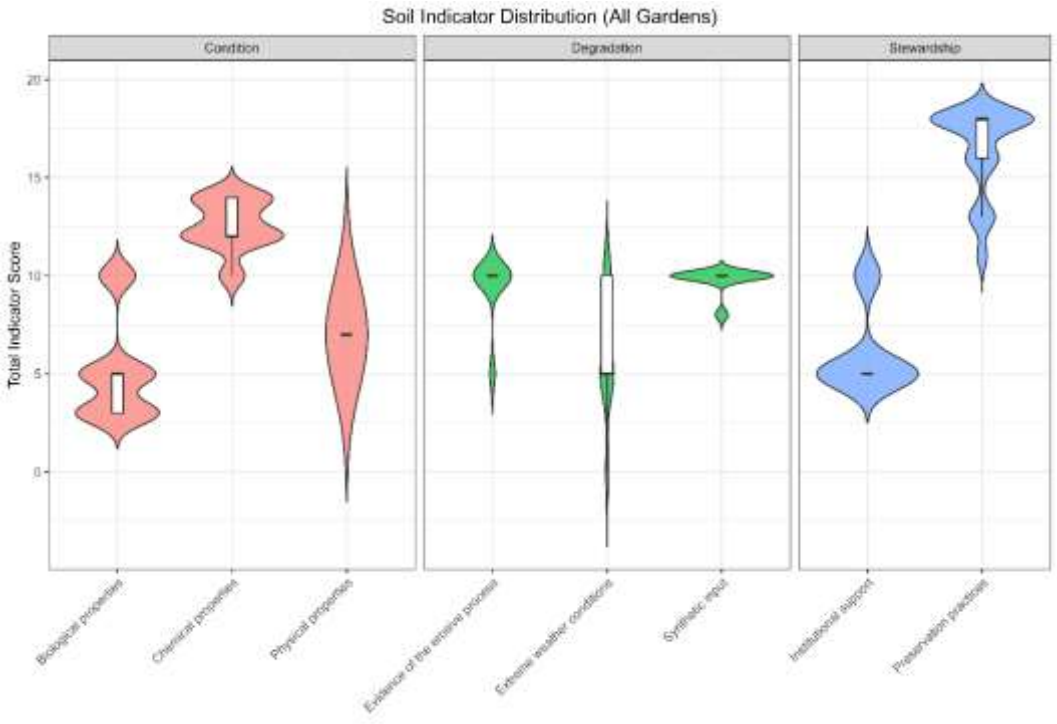

Figure 5.3. Score distribution of soil indicators across all gardens

aggregate performance and quantified practices of the 54 individual gardeners., the width of the shape (the horizontal span) at any given score on the vertical axis represents the probability density, or frequency, of the data. A subset of indicators, including *Public policy, Physical properties,* and *Land Tenure Policy*, is characterized by zero variance ($\sigma = 0$) and median scores at or near the maximum possible value (Appendix A.3.6). From the analysis, these indicators appear to function less as measurements of variable gardener choice and more as metrics of the stable, top-down institutional and biophysical platform. This platform, provisioned by the City of Nantes, has effectively secured the foundational assets widely identified in the literature as prerequisites for UFG viability. These include secure land tenure, a primary barrier to long-term investment in urban agriculture, and high-quality, safe soil conditions (as detailed in Section 3.1).

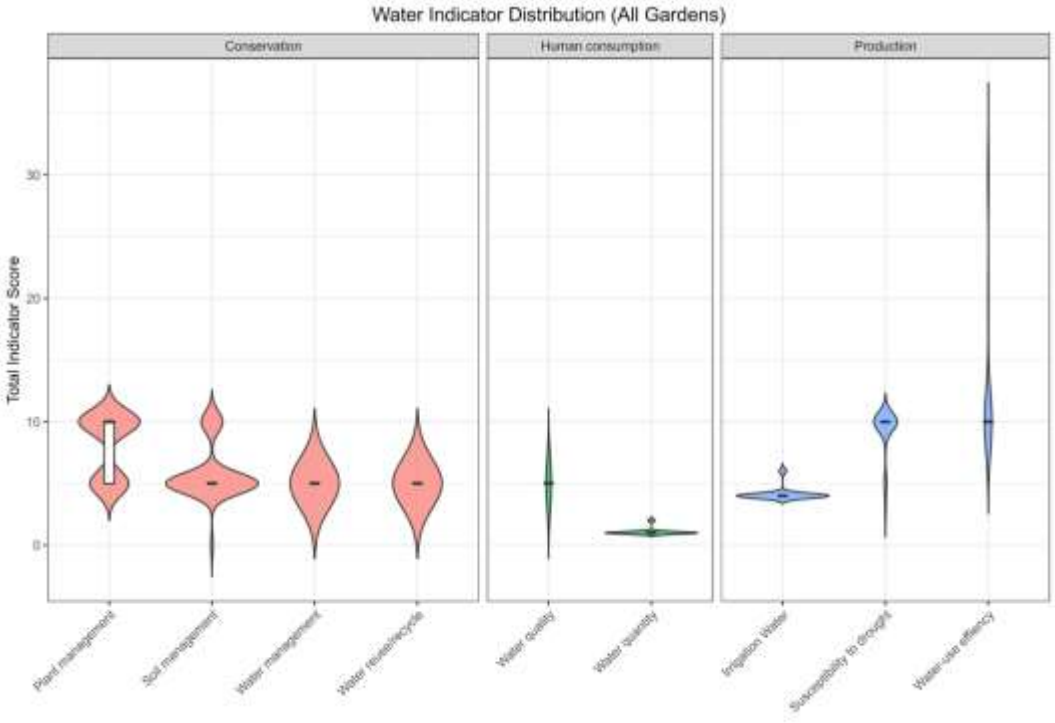

Figure 5.4. Score distribution of water indicators across all garden

A contrasting pattern emerges for indicators related to social, communal, and educational functions. This group, which includes S*ocial sharing, Tradition and culture,* and *Garden management tool*, exhibits a median score of 0 (as visually presented in Figure 5.5 and numerically detailed in Appendix Table A5). This median, coupled with high variance (σ = 2.52, 1.74, and 1.79, respectively), suggests that while a few individuals are highly engaged, the majority of participants do not perform these functions. These indicators seem to reflect the sphere of voluntary social choices, knowledge practices, and communal actions under

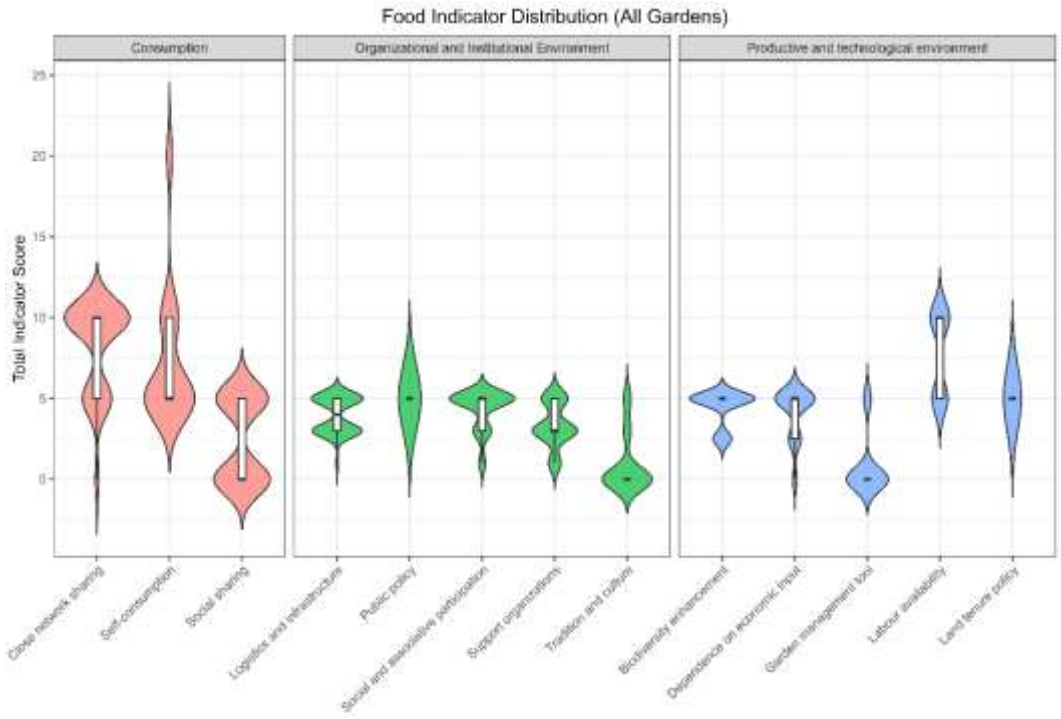

Figure 5.5. Score distribution of food indicators across all gardens

This bifurcation presents a nuanced finding: while the institutional framework is demonstrably stable and secure, this foundation does not appear to automatically catalyze the full potential for social cohesion or knowledge transfer. This

observation empirically challenges, or at least complicates, the commonly held assumption that allotment gardens are inherent drivers of social capital. Our findings align more closely with research from other French contexts, such as that of Martin *et al.* (2017) in Marseille, which found that gardeners may prioritize the individual and familial benefits of cultivation over broader communal sharing or organized social activities. This is a notable consideration for urban greening policy, which often relies on these assumed, but perhaps not universally realized, social outcomes to justify public expenditure on UFG initiatives.

A disaggregated view, moving beyond the network average, reveals significant heterogeneity among the five gardens, underscoring that not all UFG sites within the district exhibit equal performance. Figure 5.5 visualizes the distinct sustainability profiles and mean FWS scores for each garden.

- Garden AM exhibits the network's highest 'Soil' score (79.38) yet, paradoxically, one of its lowest 'Food' scores (51.81).

- Garden EG demonstrates an inverse profile to Garden AM, with one of the lower 'Soil' scores (69.91) but the second-highest 'Food' score (60.67).

- Garden AC presents a more balanced, high-performing profile with strong scores in both 'Food' (61.3) and 'Soil' (75.4).

- Garden CR is situated near the network average, combining a solid 'Soil' score (74.43) with a moderate 'Food' score (57.57).

- Garden BR registers as the lowest performer across all three axes: 'Food' (45.5), 'Soil' (64.0), and 'Water' (51.67).

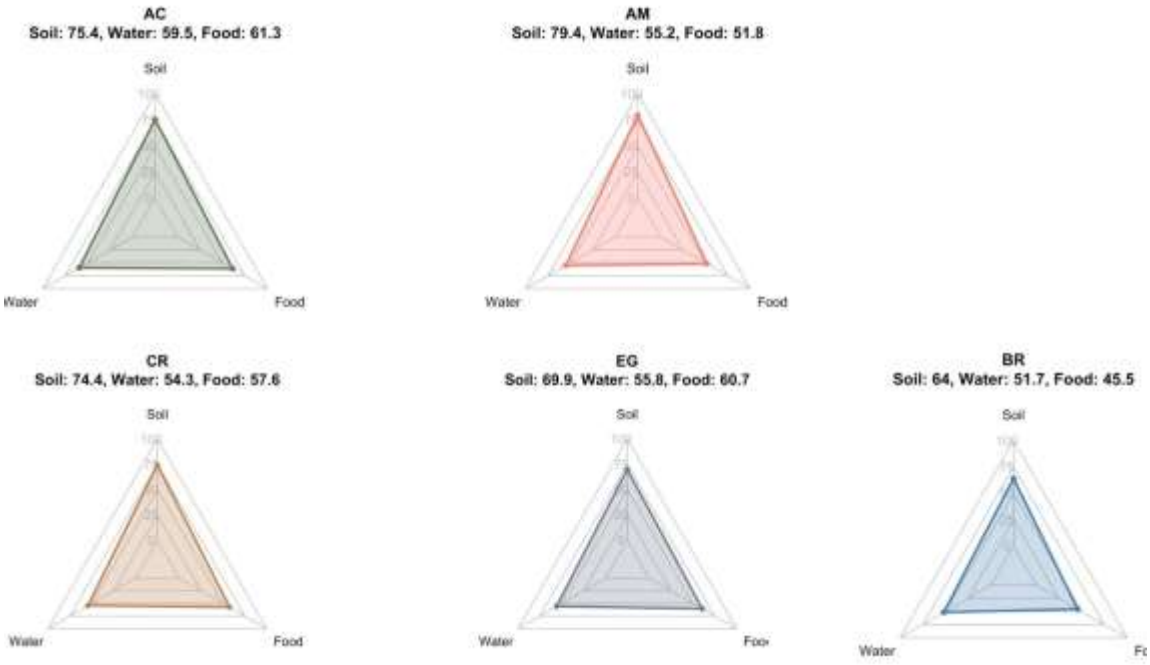

Figure 5.6. Overall FWS profile of 5 UFGs in Nantes Nord

To interpret these profiles accurately, it is helpful to recall the structure of the data. The 'Soil' axis score is substantially influenced by the 'Soil Condition' scope. As this metric was derived from a pre-existing database and applied uniformly across all plots within a single garden, it functions here as a proxy for the garden's foundational biophysical asset. Thus, AM's high score (79.38) suggests it possesses a higher biophysical (soil) endowment, while Garden BR's low score (64.0)

indicates a comparatively poorer soil foundation. This latter condition might necessitate more intensive stewardship from gardeners to achieve the same productive potential.

In contrast, the 'Food' and 'Water' axes scores are driven by the aggregation of individual, plot-level management choices (e.g. 'Crop rotation', 'Water-use efficiency', 'Self-consumption'). This methodological distinction is between a static biophysical foundation and dynamic, plot-level human practices. The comparison between Garden AM and Garden EG is particularly instructive. Garden AM appears to possess the highest-quality soil asset (79.38) but translates this into one of the network's lowest 'Food' scores (51.81), which also incorporates social-organizational elements. Conversely, Garden EG, operating on a less-advantaged soil endowment (69.91), achieves one of the network's highest 'Food' scores (60.67).

This apparent disconnect suggests that biophysical potential does not unilaterally determine socio-ecological outcomes. It seems plausible that management practices, gardener knowledge, and social organization may function as either significant bottlenecks or, in the case of Garden EG, powerful compensatory mechanisms that mediate the limitations of the physical environment. The known context of Garden EG strongly corroborates this statistical finding. This site is well-documented to have a significant soil pollution problem (Bechet et al., 2018). However, this biophysical deficit was addressed through intensive, highly

organized intervention from the City of Nantes and research institutes, which implemented remediation efforts such as phytoextraction, an accumulative cropping system experiment, and the installation of raised beds with imported soil. Furthermore, the garden's high social performance is consistent with its known role as the largest garden in the network, one that often works with local supermarkets for social causes. This context validates the finding that Garden EG's success is a product of high social and institutional agency overcoming a poor biophysical (soil) endowment. This finding aligns with core agroecological principles (Thomas and Kevan, 1993), which posit that soil function is not a static property but an emergent property of management, constantly shaped by human intervention.

5.4.2 Validation of the FWS system performance

To validate the descriptive findings and probe the hybrid-scale data structure, two non-parametric tests were applied. The Kruskal-Wallis H test was used to determine if statistically significant differences exist between the five independent gardens, while the Friedman test was used to determine if the FWS profile within a single garden was statistically unbalanced. The choice of non-parametric tests since the score data is ordinal and, as shown by the indicator violin plots (Appendix A.3), not normally distributed (e.g. bimodal, skewed, or constant).

Table 5.22 Validation of system performance (derived from significance set p<0.05)

Test type	Comparison	Axis/Garden	p-value	Interpretation
Kruskal-Wallis H	Difference *Between* gardens (df=4, N=54)	Food	0.00127	Significant
		Soil	0.00004	Highly Significant
		Water	0.52637	Not Significant
Friedman Test	Imbalance *within* each garden (df = 2)	AC	0.02024	Unbalanced
		AM	0.00150	Unbalanced
		BR	0.06948	Balanced
		CR	0.01832	Unbalanced
		EG	0.000001	Highly Unbalanced

Note: N represents the sample size (N=54 for inter-garden Kruskal-Wallis comparisons; N varies for intra-garden Friedman tests based on garden population). Df represents the degrees of freedom (Df=4 for 5 garden groups; Df=2 for 3 FWS axes). The threshold for statistical significance across all omnibus and post-hoc tests is established at p < 0.05.

5.4.2.1 FWS performance difference between gardens

The Kruskal-Wallis H test (Table 4.21) provides statistical confirmation of the heterogeneity observed between the five gardens. Highly significant differences are registered for both the 'Food' axis (set $p < 0.001$) and the 'Soil' axis (set $p < 0.0001$). This outcome aligns with the multi-scale conceptual framework. The

variance in the 'Soil' axis is logically driven by the differing local biophysical endowments ('Soil Condition') inherent to each site. The variance in the 'Food' axis captures the aggregated expression of diverse, smaller-scale 'Gardener Choices' and management practices.

Perhaps the most critical finding from this test, however, is the lack of difference in the 'Water' axis ($p = 0.526$). This result confirms that, from a statistical perspective, all five gardens share an identical water profile. This is not a methodological error but a finding that validates the hybrid-scale model. It demonstrates that the indicators within the 'Water' axis are dominated by city-level constants, such as homogeneous access to tap water and city-provided water tanks, as well as a shared regional climate. Physiologically, the input (water access) and regional context (climate) are standardized public utilities and environmental conditions for all gardeners, resulting in zero significant variance between sites.

5.4.2.2 FWS performance imbalance within gardens

The Friedman test reveals that 4 out of 5 gardens have a statistically unbalanced FWS profile $p < 0.05$. The analysis reveals that only BR is classified as "balanced.' However, the observed 'imbalance' is more indicative of the methodological limitations inherent in the hybrid-scale model than actual management deficiencies. The Friedman test assesses the rankings across three axes within each garden, but a fundamental disparity exists: the 'Soil' axis scores are

predominantly affected by low variance and site-specific factors due to standardized weights, whereas 'Food' and 'Water' axes reflect high-variance, micro-scale decisions. Consequently, the test compares inherently disparate data types, correctly detecting the significant difference between the stable 'Soil' asset and the more variable 'Food' and 'Water' practices. Post-hoc analysis confirms this pattern: in gardens AC, AM, and EG, significant differences are consistently observed between 'Soil' and each of the other two axes, whereas 'Food' and 'Water' are not significantly different from each other. These findings affirm that the 'Soil' axis functions as a structural outlier within the model.

The interpretation also explains the status of BR. Its "balance" ($p = 0.07$) is not a sign of sustainability. Instead, it represents a "low-performance equilibrium". Its mean scores (Food: 45.5, Soil: 64.0, Water: 51.67) are all clustered at a low level, making them statistically indistinguishable. This is a balance of systemic underperformance, not a model of integrated success. The garden's known institutional context strongly supports this finding of systemic underperformance. At the time of the assessment, BR had reportedly been without a functioning association board for an extended period, with new leadership just arriving. This historical lack of active leadership, social organization, and internal governance provides a direct explanation for the 'low-performance equilibrium,' confirming that dedicated garden leaders are essential catalysts for driving social cohesion and equity." With no coordinating agency to drive stewardship, knowledge transfer, or communal activity, the choices defaulted to a low-performing

baseline, bringing the 'Food' and 'Water' scores down to the level of its already-poor 'Soil' endowment.

5.4.3 Nantes Nord UFGs' sustainability performance

The final stage of our analysis re-synthesizes all 37 FWS indicators into the five core MESMIS sustainability attributes: Productivity, Stability, Adaptability, Equity, and Self-Management (as defined in Section 3.3). This re-classification moves the assessment from measuring components (Food, Water, Soil) to measuring systemic functions. This normalized (0-100) assessment quantifies the functional performance of the UFG network as a social-ecological system. The mean normalized scores for the entire Nantes Nord network are visualized in the 5-

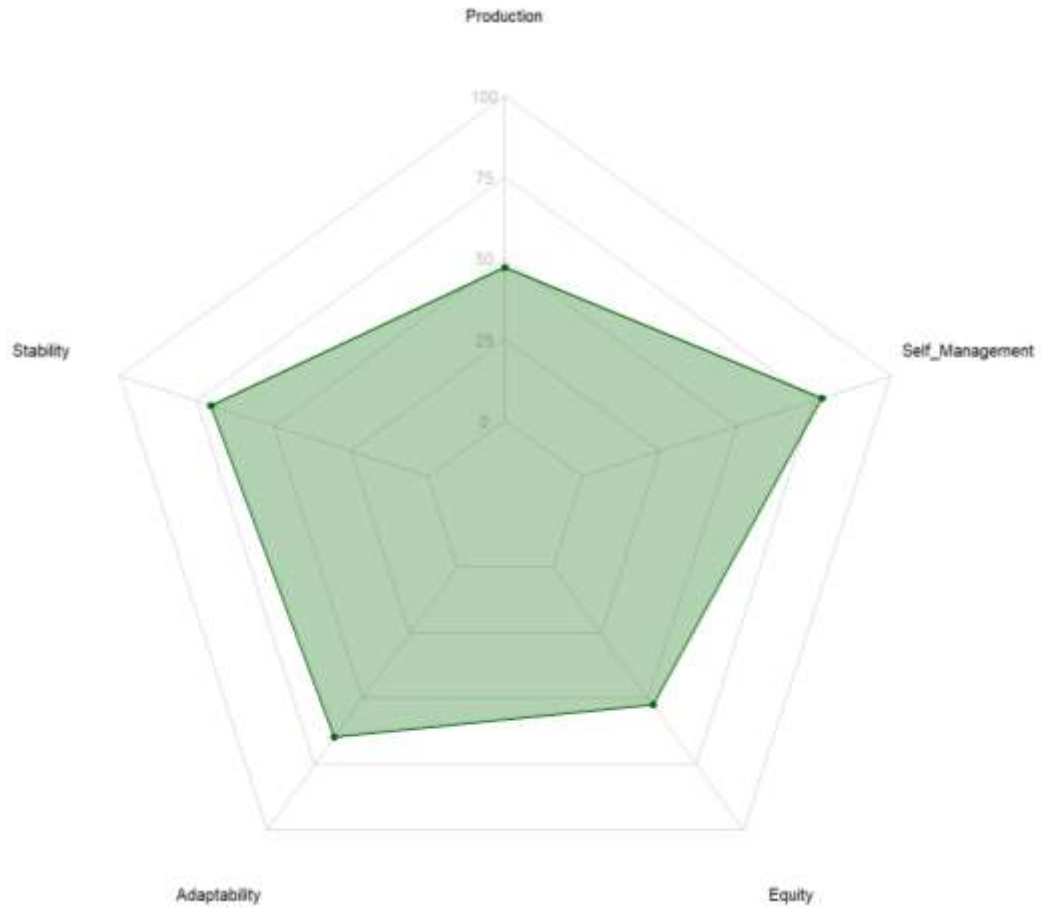

Figure 5.7. Overall performance of UFGs' sustainability attributes in Nantes Nord

attribute radar chart (Figure 5.6). The results present a clear divergence in systemic performance, with high performance in Self-Management (77.7) and Stability (70.4); moderate performance in Adaptability (64.6); and low performance: Equity (52.5) and Production (47.0)

From the results, it seems that the Nantes Nord UFG system is structurally sound but operationally and socially underperforming. The system is stable and autonomous, but it is failing to deliver on its core functions of productivity and social equity as an NbS. The two highest-performing attributes, *Self-Management* and *Stability*, could likely be the results of effective top-down and endowed structure. *Self-Management's* high score is driven by the indicators that define the secure, top-down governance platform. Its constituent indicators include *Public policy*, *Land tenure policy*, and *Soil pollution intervention*. These are the institutional guarantees that give the system its autonomy. Meanwhile, Stability's high score is built upon the system's biophysical endowment. Its most heavily-weighted components are the *'Soil Condition*' indicators.

The two attributes with the lowest performance, *Equity* and *Production*, are due to their heavy reliance on human agency. *Equity* ranks second-lowest because its score is significantly affected by the "social deficit" indicators, which include Social sharing and Tradition and Culture, areas where the five gardens generally received low scores. Production is the lowest attribute overall, consisting entirely of indicators influenced by personal choices, such as Self-consumption. The median

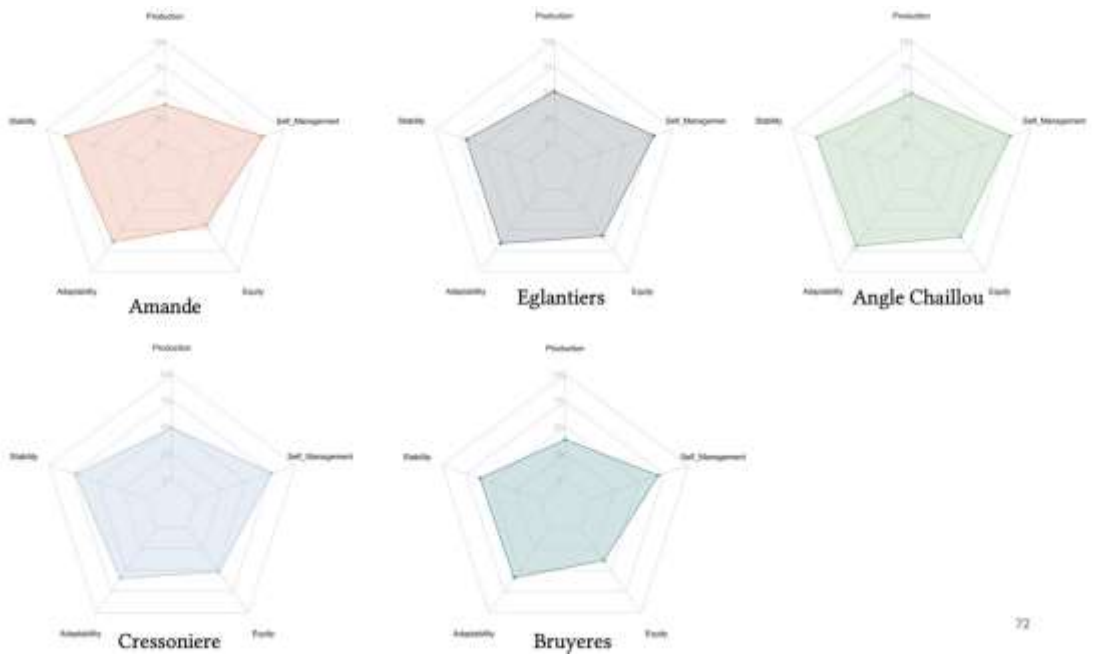

Figure 5.9. Overall performance across 5 UFGs' sustainability attributes

score for Self-consumption was 5, well below the maximum of 20, with respondents noting that cultivated vegetation can only replace a small part of the market's vegetative products—about 20%. Additionally, *Production* is negatively impacted by poor Water-use efficiency, as many gardeners opt for low-scoring "conventional" farming systems.

Figure 5.7 provides a detailed look at the sustainability performance of each garden. Among them, AC performs consistently well across the board, scoring near the top in Adaptability (69.2) and Equity (58.0), and second-highest in Stability (74.4). It has no significant weaknesses, presenting the most balanced, high-performing profile. Meanwhile, Garden AM has a profile defined by a clear trade-off. It is the undisputed leader in Stability (79.1), scoring significantly higher than

any other garden. However, it has a lower performance in Production (38.3) and Equity (44.2). This suggests a focus on ecological resilience and stewardship over socio-productive outcomes. BR is the clear underperformer. It scores last or second-to-last in all five attributes, with the lowest scores in Stability (61.2), Equity (38.3), and Self-Management (69.5). Garden CR shows another trade-off. It is a strong performer in Production (49.0), but has the lowest score in Adaptability (59.9). This may indicate a more rigid, conventional production system that is less resilient or flexible. Garden EG demonstrates a profile that is the inverse of AM. It is the top performer in Production (50.9) and Self-Management (79.8), and second-highest in Equity (56.8). Its primary weakness is a relatively low Stability (67.3) score.

5.5 SYNTHESIS

5.5.1 Recalibrating the nexus approach

This dissertation has, in Chapter 4, presented the empirical results of an assessment of UFGs in Nantes Nord. This final chapter now transitions from the presentation of those findings to their interpretation and synthesis. It serves as the keystone of the dissertation, evaluating the central hypothesis that a meaningful assessment of UFGs as a form of NbS requires a fundamental paradigm shift away from conventional assessment models.

The literature review in Chapter 2 systematically mapped the landscape of UFG assessment tools, identifying a critical gap. It revealed a field dominated by five distinct methodological clusters, but also a persistent theoretical challenge: the dominant WEF nexus, a powerful paradigm in large-scale resource management, is not a well-fit framework for the UFGs. The WEF nexus, born from a macro-scale, engineering, and resource-security perspective, is often "treating soil simply as a passive substrate. Furthermore, its focus on quantifiable biophysical flows struggles to capture the complex social, cultural, and political processes that define the success or failure of community-managed spaces.

The development of the FWS nexus in Chapter 3 was the dissertation's primary theoretical corrective to this gap. This new framework was proposed as a considerable remodelling of nexus thinking. It achieves this in two ways:

1. Explore the theoretical framework to replace 'Energy' component with the 'Soil' component, explicitly re-centring the assessment on soil as the foundational living infrastructure and capital asset whose health governs the system's core functions
2. Employ the dual lenses of ES and EDS as its primary analytical tools, shifting the assessment from a simple accounting of material flows to a qualitative and quantitative evaluation of the system's socio-ecological performance and its net contribution to human well-being.

This discussion now uses the empirical findings from Nantes, both the quantitative application of the FWS Sustainability Index (Chapter 5 results) and the qualitative perception study (Chapter 4), to evaluate the successes and failures of this operating framework. This chapter, therefore, holds two objectives: to interpret the state of the object to study (the Nantes UFGs as NbS) and to appraise the utility, validity, and limitations of the tool this dissertation created to study.

5.5.2 UFGs in Nantes Nord as a nature-based solution

5.5.2.1 Role of institutional platform in the success of NbS project

The MESMIS-FWS index results show high performance in the two attributes related to systemic stability and autonomy: Self-Management (77.7) and Stability (70.4). This finding of a stable, autonomous system is a notable success. However, a deeper analysis of the indicators comprising these attributes shows that this strength is not an emergent property of gardener action. Instead, it is the direct, causal result of a robust, top-down institutional platform provisioned by the City of Nantes.

The high Self-Management score is driven by indicators that function as institutional constants: Public policy and Land tenure policy. These indicators had zero variance (Appendix B.3.6), with all 54 gardeners receiving the maximum

score. This demonstrates that the city has successfully provided the single most critical prerequisite for sustainable urban agriculture: secure land tenure. This policy removes the precarity that plagues many UFGs and empowers gardeners to invest in their plots for the long term.

Similarly, the high Stability score (70.4) is not a reflection of superior gardener stewardship. It is largely an artifact of a biophysical endowment. The score is heavily weighted by the Soil Condition indicators (Physical, Chemical, and Biological Properties), which, as noted in the methodology, were averaged from pre-existing data sets. These data show that the gardens are, for the most part, situated on high-quality, safe soil. Thus, the FWS index confirms that the city has successfully provisioned the two foundational assets of a UFG: secure land and healthy soil.

5.5.2.2 Mismatch of tool and policy

The system's robust structural design sharply contrasts with its low scores in attributes reliant on human agency and social interaction, specifically, Equity (52.5) and Productivity (47.0). While a superficial interpretation might view these as social shortcomings or gardeners' deficiencies, a more nuanced analysis suggests that these scores reflect limitations in the assessment framework and policy model rather than system failure.

First, the low "failing" Productivity score (47.0) is a methodological artifact rooted in the MESMIS-FWS index, which concentrates on food provision, such as self-consumption, originally designed for evaluating farming systems. The score reflects gardeners' reports that their plots supply only a small portion of market vegetables, but this is not indicative of failure. As discussed earlier, the system does not aim to replace markets; gardeners primarily value well-being and ecological stewardship, covering health, social cohesion, biodiversity, and education. It demonstrates that urban gardens are esteemed for their multifunctionality rather than provisioning. Hence, the low Productivity score highlights a mismatch: it penalizes the system for not meeting a goal it does not pursue.

Second, the low Equity score (52.5), rooted in the near-zero performance of indicators such as Social sharing scores (median of 0), should be reinterpreted not as a moral shortcoming of the gardeners but as an empirical challenge to the policy model. The presence of green space alone does not spontaneously generate social benefits such as cohesion or community engagement; these require active facilitation and management. For instance, the higher social performance score of EG likely results from its scale and strategic partnerships with external civic groups, rather than emergent properties. Similarly, the low equity score reflects a policy gap rather than a user deficit.

This reinterpretation elucidates the "perception-practice gap" identified in the research. Chapter 4's findings reveal that gardeners prioritize social and educational benefits, rating these as "Highly important" (Median=4), forming the basis of the "Well-being" and "Ecological Stewardship" frameworks that underpin their worldview. Conversely, Chapter 5's FWS index indicates minimal translation of these values into practice, with Social Sharing scoring a median of 0. This disparity suggests a lack of structural support for transforming gardeners' latent social and educational aspirations into action, despite their receptivity and unmet demand for such benefits.

5.5.2.3 From urban garden to urban nature-based solution

The NbS policy in Nantes Nord currently adopts a passive approach, relying on infrastructure and institutional assets (e.g. secure land, clean soil, water access), assuming social benefits such as cohesion, equity, and knowledge transfer will naturally follow. To enhance effectiveness, the strategy requires active engagement, targeting the "social deficit' as the primary leverage point. Investments should shift from the existing physical infrastructure to the social dynamics underpinning these gardens, specifically funding social processes that bridge the perception-practice gap. This includes resources for part-time coordinators or animators tasked with orchestrating community activities, workshops, and donation drives—interventions currently absent. Strengthening support for local nonprofits like ECOS and MAAD could further amplify social

cohesion within Nantes Nord; they were identified in the research as important actors fulfilling this social role.

A central aspect of active catalysis involves establishing institutional linkages that transform gardens from isolated plots into integrated community assets. Data indicate strong community valuation of education (Median=4, IQR=0.75), yet knowledge transfer related to tradition and culture remains minimal. The city could facilitate partnerships between garden groups and local schools, effectively designating gardens as living classrooms and open learning environments. Such initiatives would foster intergenerational engagement and environmental literacy, moving beyond passive observation. The low scores in Equity (52.5) and Productivity (47.0) are primarily attributable to a near-absence of social sharing (Median=0). This approach is not aimed at commercialization but at creating equitable pathways for surplus produce distribution. The success of Garden EG exemplifies this model; despite lower soil quality scores, its specifically established to recover unsold organic food/waste for community composting/consuming supports its broader circular and community-oriented goals.

5.5.3 Evaluation of the FWS nexus assessment framework

5.5.3.1 Functionality of the framework as a theoretical and diagnostic tool

As a theoretical corrective, the FWS nexus framework is shown as a promising model. It addressed the primary critiques of the WEF nexus identified in the literature review. By replacing the 'Energy' component with the foundational 'Soil' component, it provided a paradigm that is ecologically appropriate for a soil-based NbS. It grounded the nexus in its material foundation, aligning with calls from soil scientists to place soil at the center of sustainability assessments.

More importantly, the framework demonstrated its power as a diagnostic tool, capable of revealing complex socio-ecological phenomena that a simple resource-flow model would overlook. For example, in the case of garden BR, a standard WEF or LCA model, focused on biophysical flows, would merely register "low productivity" and "low efficiency." The MESMIS-FWS model, however, by integrating social-institutional indicators (e.g. Social and associative participation), was able to diagnose this as a failure of social governance correctly. The field context confirmed this garden had been without a functioning association board, leading to a "low-performance equilibrium". This demonstrates the framework's unique power to link social and biophysical domains and identify the correct (in this case, social) point of intervention.

Furthermore, the theoretical choice to build the framework around the dual lenses of ES and EDS was empirically validated by the perception study. The framework was designed to account for disservices as critical components of the system. The survey data then confirmed that key disservices, namely Water Consumption and

Soil Pollution, were, in fact, the gardeners' primary and most widely shared anxieties. This confirms that the FWS framework is not just theoretical but is aligned with the lived reality and perceptions of the actors involved in UFGs themselves.

5.5.3.2 Limitations of the methodological approach

Despite its successes, the practical application of the MESMIS-FWS framework remains imperfect. As a data-intensive tool, it demands 37 distinct indicators derived from 43 survey questions and a complex soil database. While the underlying philosophy of MESMIS is appealing, its implementation is inherently complex, resource-heavy, and demanding of detailed data—challenges encountered throughout this dissertation.

As detailed in Chapter 5's methodology section, the requirement for plot-level soil data exceeded the project's scope. Consequently, reliance on an existing soil database introduced the "spatial misalignment" compromise: soil samples did not correspond precisely to the surveyed plots.

To address this issue, soil condition data were averaged at the garden level, producing a single score assigned uniformly across all plots within the same garden. This averaging, dictated by the framework's data demands, fundamentally undermined its premise. It generated a statistical homogeneity along the 'Soil' axis, which influenced later results.

MESMIS was selected for its participatory, bottom-up, context-specific approach. However, its complexity and data requirements ultimately necessitated a retreat to a top-down, technocratic methodology, an approach that contravened the framework's foundational philosophy. This discrepancy highlights the persistent tension between methodological idealism and practical constraints, serving as a cautionary tale about the challenges of operationalizing holistic approaches within limited-resource settings.

Additionally, the primary issue lies in the discrepancy between the perceived objectivity of the index's weights, presented in Chapter 5, and their underlying subjectivity rooted in normative judgments. Although the original MESMIS methodology claims that weights were derived from "expert opinions of the research team," "literature," and "perceptions of the participant," these justifications are often applied retrospectively. For example, the weighting of the 'Water' axis exemplifies this problem: production (water for crops) is assigned 50 points, whereas human consumption (water for gardeners) receives only 10 points. Such subjective weighting methods are a fundamental critique of composite sustainability indicators (Gan et al., 2017), as they can embed implicit biases and generate misleading results. Ultimately, the final scores are as much shaped by these initial subjective decisions as by the actual data, raising concerns about the validity of work related to composite indicators.

Sustainability assessment often involves summarizing scores; without careful investigation, the index is prone to compensability—a high score in one indicator can cancel out (or "compensate for") a low score in another. This is not just a statistical operation; it is a well-debated topic in environmental science (Purvis and Genovese, 2023). Critical arguments revolve around the relevance of indicators, the “expert” who determines indicators’ weights, and technical issues in aggregation.

Finally, the min-max normalization method used by the index is known to be highly sensitive to extreme values and outliers. It creates what is known as an "imbalance between scores and rankings", where the final profile is a fragile artifact of the normalization method. The index, therefore, besides simply reporting on reality, is prone to creating a reality that is sensitive to its own methodological choices.

5.5.4 Future research and direction

The limitations acknowledged in this analysis delineate a clear and necessary agenda for future research, which must evolve from methodological development to practical refinement and intervention-based science. A primary methodological gap is the current disconnect between perception and biophysical reality. The logical successor to this work must be a true plot-level investigation that empirically connects (1) an individual gardener's perceptual framework and stated values, to (2) their actual, observable management practices (e.g. tillage frequency, composting methods, irrigation type), and ultimately to (3) the measured biophysical outcomes on their specific plot (e.g. soil organic carbon, water retention, heavy metal concentrations). Such a study would forge the critical link between the social and the ecological, providing a high-resolution dataset to validate the socio-ecological feedback loops that are central to the FWS nexus.

Methodologically, the proposed FWS Sustainability Index must also be advanced from a top-down model to a collaborative tool. As presented, its "expert-defined" weights risk rendering it a technocratic "black box," opaque to gardeners it is meant to serve. Future work must "open" this box by developing a participatory weighting system. Employing established methods, such as the Analytic Hierarchy Process (AHP), to engage diverse stakeholders, from gardeners themselves to municipal planners and association leaders, in the process of assigning value

would be transformative. This would elevate the index from a static report into a true "boundary object": a shared, legitimate, and socially-negotiated tool for the co-creation of sustainability goals.

Furthermore, a primary methodological imperative for future research is addressing the 'black box' limitations inherent in complex composite indicator aggregation. The current FWS framework relies on 37 indicators, creating a substantial data collection burden for urban stakeholders. To optimize this, future iterations must incorporate sensitivity and uncertainty analyses (Saltelli et al., 2019), which are recognized as essential tools for the quality assessment of composite indices . By systematically applying variance-based sensitivity analyses (Saisana et al., 2005), researchers can quantitatively evaluate how fluctuations in individual criteria weights influence the final sustainability attributes. This analytical process will identify the specific variables that drive the most significant systemic variance, allowing for the safe removal of redundant or low-impact indicators. Ultimately, this distillation process will yield a validated Minimum Dataset, potentially transforming the FWS index from a data-heavy academic model into a streamlined, efficient diagnostic tool for urban planners.

Lastly, this analysis suggests that key failures may stem from policy and resource deficits, not a lack of social will. Future research must therefore pivot from passive assessment to active intervention. This implies a research agenda focused on co-designing and testing specific policy interventions, for example, funding a part-

time garden coordinator to address the social Equity attribute of the MESMIS framework. The refined, participatorily-weighted FWS index would then be operationalized as the primary monitoring tool to evaluate the intervention's success over time quantitatively. This approach would complete the adaptive management cycle, creating a tangible, evidence-based pathway for integrating soil health policy with social justice policy to build truly resilient and equitable urban socio-ecological systems.

5.6 CONCLUSION

This chapter has detailed the operationalization of the Food-Water-Soil (FWS) Sustainability Index, a novel framework developed to address the persistent gap in assessing urban food gardens as complex Nature-based Solutions. The work began from a central premise: that the dominant WEF nexus, with its macro-scale and flow-based logic, is an ill-fitting paradigm for these soil-based ecosystems, often treating soil as a passive substrate. Our FWS nexus was proposed as a necessary theoretical corrective, repositioning soil as the foundational, dynamic capital asset that governs the system's socio-ecological performance.

The contribution of the FWS Sustainability Index is threefold, reflecting the integrated logic of this dissertation. First, reflecting the integrated logic of this dissertation. First, it is theoretically grounded in the soil-centric FWS nexus, a paradigm that identifies soil not as a passive input but as the central, dynamic

capital asset governing the system's performance. This provides a coherent conceptual basis for assessment that aligns with the biophysical realities of UFG.

Second, the index is built upon the proven, process-oriented MESMIS framework. This heritage ensures that the assessment is systemic, cyclical, and philosophically aligned with the principles of adaptive management and participatory evaluation that are essential for complex systems. While the final mathematical normalization and aggregation of the index ultimately necessitated expert-led parameters, the foundational selection and structural weighting of the Food, Water, and Soil indicators were directly anchored in the empirical, participatory survey data gathered from the 54 local gardeners. This integration ensures that despite top-down mathematical constraints, the framework's diagnostic priorities remain firmly grounded in the lived experiences and valuations of the community.Most critically, the index is informed. Its structure, indicators, and weighting scheme are not abstract constructs but are validated by the expressed values, concerns, and shared worldview of the stakeholder community in Nantes. The direct linkage between the gardeners' perceived priorities, such as their profound concern for water consumption and their integrated view of social and productive well-being, and the final weights assigned within the index demonstrates a synthesis of top-down expertise and bottom-up opinion.

Ultimately, the FWS Sustainability Index is more than an assessment tool; it is a governance instrument. By providing a data-driven engine for an adaptive

management cycle, it offers a practical pathway for moving urban greening policy beyond simple aesthetics or provision. It enables a more integrated, evidence-based approach that fosters a continuous dialogue between managers, gardeners,

CHAPTER 4 SUMMARY

- **Methodology**: Application of the MESMIS-FWS Sustainability Index, utilizing 37 specific indicators across 5 garden sites. Data was normalized to standardized percentages and analyzed via Kruskal-Wallis and Friedman test.
- **Key Results**: Generated a quantitative diagnostic profile revealing a structural dichotomy in the gardens: high performance in stability and self-management (driven by municipal institutional support) but low performance in equity and productivity (highlighting a gap in grassroots and social sharing).

6 CONCLUSION AND RECOMMENDATION

6.1 INTRODUCTION

This chapter serves as the capstone of my doctoral research, weaving together the theoretical, methodological, and empirical threads of the preceding chapters into a cohesive whole. It revisits the central problem that motivated this thesis: UFGs are increasingly recognized as vital NbS for enhancing urban resilience, yet the dominant assessment paradigms, particularly the WEF nexus, are fundamentally unfit for these low-energy, soil-based systems. As my research has demonstrated, these frameworks often marginalize the foundational role of soil, treating it as a static substrate rather than the dynamic capital asset it truly is.

The primary aim of this dissertation was to address this critical gap by formulating, developing, and validating a novel FWS nexus framework. It re-centers the assessment on the correct biophysical foundation, soil as a living, dynamic capital asset, and employs the correct analytical lens, evaluating the system's functional performance through the ES and EDS it co-produces.

This dissertation argues that the FWS nexus and its operational tool, the FWS Sustainability Index, represent a notable contribution to both sustainability science and urban governance.

By re-grounding nexus thinking in the material reality of the urban edible network, this work offers a more relevant and socially informed approach to assessment. It provides a quantitative, diagnostic understanding of their performance, thereby enabling more strategic management and evidence-based policy.

This section serves as a roadmap for readers. The chapter progresses through a series of structured reflections, beginning with a recapitulation of the research development, tracing the logical arguments from problem identification in the literature to the creation of a practical, validated tool. This is followed by a critical discussion of the research's broader relevance, its inherent strengths, and, just as importantly, its limitations. It presents a forward-looking outlook with concrete implications for future research and for policy and practice, with a specific focus on the city of Nantes. Finally, a concluding statement will crystallize the core message of this work: that the path to a resilient urban future depends on re-grounding our sustainability assessments in the living soil and in the lived experiences of the communities who steward it.

6.2 RESEARCH TRAJECTORY AND KEY FINDINGS

This section retraces that trajectory, demonstrating how the systematic identification of a research gap led to the development of a new theoretical framework, which was then empirically grounded and finally operationalized into a practical assessment tool.

The research began in Chapter 2 with a systematic review of the landscape of integrated assessment tools for UFGs. The analysis mapped the field into five distinct methodological clusters: Quantitative Sustainability Assessment, Spatial Planning & Optimization, Systems & Nexus Modeling, Socio-Ecological & Community Assessment, and Empirical & Field-Based Studies. While this mapping provided a useful typology, its most notable finding was the exposure of a systemic weakness across all paradigms. The review revealed a critical and persistent disadvantage of existing frameworks, including the popular WEF nexus, to adequately "re-ground" assessments in the dynamic, living dimension of soil. Across the 58 papers analysed, soil was consistently treated as a passive substrate, a static variable in a spatial model, an abstracted input in an LCA, or was absent from nexus simulations altogether. This chapter’s primary function was diagnostic; it empirically established and precisely defined the theoretical and methodological gap that the remainder of the thesis would seek to fill.

In direct response to the gap identified in Chapter 2, Chapter 3 was dedicated to developing the theoretical architecture of the FWS nexus. This chapter argued for a fundamental paradigm shift, one that repositions soil from the periphery to the very centre of the analytical framework. I conceptualized soil not as a simple input but as the central mediating component — a capital asset whose health and functional state govern the system's overall

performance and resilience. To analyse the complex interactions within this nexus, I employed the dual lenses of ES and EDS. This approach allowed the analysis to move beyond a simple accounting of material flows to capture the qualitative, functional outcomes of the garden system as they relate to human well-being. The chapter culminated in a proposed management hierarchy, adapting the work of Vaz *et al.* (2017) to provide a structured, step-by-step process for the adaptive governance of FWS interactions, addressing challenges from soil contamination to water scarcity.

To ensure the FWS framework was not merely a theoretical abstraction, Chapter 4 was dedicated to grounding its core concepts in empirical, social reality through an in-depth case study of 54 urban gardeners in Nantes Nord. This mixed-methods study systematically deconstructed the gardeners' worldview, using a multi-phase statistical analysis to model their perceptions of the benefits and drawbacks of their gardens. The exploratory factor analysis revealed that the gardeners' complex belief system could be synthesized into four fundamental and statistically coherent bundles: Nuisance (personal discomforts), Ecological Stewardship (an appreciation for the garden's ecosystem functions), Pollution (a specific anxiety about chemical contamination), and Well-being (a holistic integration of physical, mental, social, and provisioning benefits). This chapter provided two critical validations. First, it proved that the ES/EDS lens theorized in Chapter 3 was socially relevant, as stakeholders do, in fact, perceive their environment in these functional terms. Second, it provided the essential social data that would justify the design of the final tool, revealing that "Water Consumption" was the community's single greatest anxiety (Median = 4, IQR = 1.00) and that "Social Cohesion" and "Education" were paramount values (Median = 4). This study also offers a complementary insight into the larger body of scientific research on urban gardens. While

Kirby *et al.* (2021) study found a homogeneity in perceived values across urban agriculture types in Europe and the US, this study found a similar pattern across sites in Nantes Nord but variance in social identity (i.e. gender of gardeners, as detailed in the comparative analysis of Chapter 4). It reinforces the importance of different needs, values, and perceptions of risk in different social groups within a single project type; therefore, it advocates for equitable planning for urban development.

The final empirical step, presented in Chapter 5, was to synthesize this work into a tangible, applied output: the FWS Sustainability Index. This chapter detailed the operationalization of the FWS nexus by critically adapting the established, participatory MESMIS methodology. The key contribution, and the completion of the social-ecological cycle, was the direct integration of the empirical findings from Chapter 4 into the design of the tool. The final weights assigned to the index's indicators, for instance, the high weight given to water conservation, were explicitly justified by the values, concerns, and perceptual bundles expressed by the Nantes gardener community. The application of this validated index then yielded the dissertation's key diagnostic findings: an internal dichotomy between high-performing institutional assets (e.g. land tenure policy) and low-performing social agency (e.g. social sharing).

6.3 STRENGTHS OF THE RESEARCH

Upon reflection, I identify three primary strengths that underpin the contribution of this dissertation. First, the core strength is the theoretical innovation of the FWS nexus itself. By replacing the 'Energy' component of the dominant WEF nexus with 'Soil', the framework offers a more accurate and physiologically relevant paradigm for a vast and growing class of

low-energy, soil-based urban ecosystems, including not only UFGs but also parks, bioswales, and other forms of green infrastructure. This is not simply an adaptation but a fundamental shift in nexus thinking. It positions a living ecosystem, soil, as the central, dynamic capital asset that mediates resource flows, rather than treating it as an external factor or a passive substrate. This shift provides a more robust conceptual foundation for understanding and managing these systems.

Second, a unique strength lies in the thesis's methodological coherence and integration. The research was designed to follow a complete and logical scientific arc, progressing systematically from one stage to the next. It began by empirically identifying a gap in the existing literature (Chapter 2), proceeded to propose a novel theoretical solution to fill that gap (Chapter 3), then grounded that theory in rich, empirical social data from a specific community (Chapter 4), and finally, synthesized all preceding work to operationalize the framework into a practical, validated tool (Chapter 5). This integrated, multi-stage design creates a powerful, self-reinforcing argument where each chapter validates and informs the next. This structure is more robust and comprehensive than a simple collection of disparate studies, demonstrating a complete cycle of scientific inquiry from problem to solution.

Third, and perhaps most significantly, the research is distinguished by its participatory and socially grounded assessment approach. The decision to base the indicator weights in the FWS Sustainability Index (Chapter 5) directly on the empirically derived perceptual bundles from the Nantes gardeners (Chapter 4) is a direct answer to the well-documented limitations of top-down, purely technocratic assessment models (Chapter 2) that often fail to capture local values and priorities. This approach is a practical embodiment of the participatory ethos of the MESMIS framework and the principles of knowledge co-production, which call for the

active engagement of stakeholders in the creation of knowledge and tools that affect them. This integration of stakeholder values enhances the index's legitimacy, its social relevance, and, ultimately, its potential for genuine uptake and use by the communities it is designed to serve.

6.4 LIMITATIONS

While this research makes several important contributions, it is also bounded by specific methodological choices and conceptual frameworks that create limitations and open avenues for critical reflection.

From a methodological standpoint, the systematic review in Chapter 2, while robust in its PRISMA-guided process, was constrained by its reliance on the Web of Science core collection and its focus on English-language articles. Furthermore, its deliberate exclusion of commercial urban agriculture models, while necessary for analytical clarity, means its findings on assessment tools may not fully capture the state of the art in that rapidly evolving sector. Similarly, the empirical study in Chapter 4 is based on a relatively small sample size (n=54). The demographic profile of this sample is also heavily skewed towards older adults, with 85% of respondents aged 55 or older. As discussed in that chapter, this group represents a "self-selected community of practice," which implies that the specific findings on gardener perceptions in Nantes Nord may not be generalizable to the broader urban population or to gardening communities in different cultural contexts.

Beyond these practical limitations, the implementation of the MESMIS-FWS framework in Chapter 5 revealed a significant tension between methodological idealism and practical

constraint. The MESMIS philosophy is participatory, bottom-up, and context-specific. However, its data-intensive nature forced a "methodological compromise." Most notably, the requirement for plot-level soil data exceeded the project's scope, necessitating a reliance on pre-existing data. This led to a spatial misalignment, as the soil samples did not correspond to the exact plots of the interviewed gardeners. The solution (i.e. average soil condition data at the garden level) was a technocratic, top-down act that masked intra-garden variability and fundamentally contradicted the hyper-local, bottom-up ethos of the framework. This highlights the persistent challenge of operationalizing holistic frameworks, which can be resource-heavy and complex.

Furthermore, while I have argued that the index's weighting is tied to the social context, it remains a composite indicator. The aggregation of 37 distinct indicators into a single score is still subject to the well-documented subjectivity of weighting critique. The process of normalization and aggregation is a subjective choice that allows for "compensability", where a high score in one area (such as good soil) can hide a critical failure in another (such as no social sharing). The final index, therefore, remains a "fragile artifact" of its own design.

Finally, the most profound conceptual limitation is what I term the political ecology blind spot. My thesis, in its focus on the internal social-ecological functioning of UFGs, largely frames them as positive catalysts for urban renewal. However, in doing so, it does not adequately engage with the large and critical body of literature on "green gentrification". However, this scope is outside of our research proposal.

6.5 OUTLOOK: IMPLICATIONS FOR RESEARCH, POLICY, AND PRACTICE

6.5.1 Implications for Future Research

This dissertation lays the groundwork for several promising avenues of future research that can build upon and extend its contributions. First, the most appropriate task is to conduct a true, plot-level investigation. Future research must pair the survey and index with plot-specific soil sampling. This would fix the "spatial misalignment" and forge the critical empirical link between an individual gardener's stated values, their observable practices, and the measured biophysical outcomes on their specific plot.

Second, the conceptual power of the FWS nexus should be tested by expanding its application to other soil-based NbS. Urban parks, bioswales, green roofs, and constructed wetlands are all ecosystems where soil health is a critical, yet often overlooked, determinant of performance. Applying the FWS logic to these systems could help to develop a more unified theory for assessing the role of soil in urban ecosystem functioning, providing a common language for planners and ecologists. While FWS can function as a foundational concept, there is a need for more assessment and operating frameworks for the FWS nexus.

Third, and most importantly, future research must directly address the limitation of the political ecology blind spot by integrating a social and environmental justice lens. This would involve augmenting the existing framework with indicators that explicitly measure social equity outcomes, such as housing affordability trends, land tenure security from building programs for gardeners, and the risk of residential displacement in the surrounding

neighbourhood. Such a tool would create a more holistic assessment that evaluates not only the ecological sustainability of green spaces but also their contribution to a just and equitable city.

6.5.2 Implications for Policy and Practice

One of the primary objectives of this research was to generate actionable knowledge. The empirical findings from Chapter 4, in particular, provide a direct, evidence-based roadmap for municipal action in Nantes. The policy implications derived from this work are not generic; they are tailored to the specific, expressed needs and values of the city's gardening community.

The analysis in Chapter 4 revealed that "Water Consumption" is the single greatest and most uniformly shared concern among gardeners.[1] At the same time, "Education" and "Social Cohesion" were among the most highly valued ecosystem services, and the data showed clear gendered differences in the perception of risks and care-related services. These findings point to a set of targeted interventions:

- **Target Water Scarcity:** The Nantes Métropole should prioritize investments and policies that directly address the community's primary anxiety. This could include subsidizing the installation of larger rainwater harvesting systems in allotment gardens that have sufficient surface areas, creating pathways for water reuse/recycle, and co-developing a series of practical, hands-on educational workshops with expert local groups like ECOS on topics such as drought-tolerant crop selection, mulching techniques, and efficient irrigation practices.

- **Amplify Social and Educational Roles:** The city should recognize and increase its support for the non-profit organizations (such as MAAD and ECOS) that are instrumental in turning small garden communities into hubs for social cohesion and learning, especially those that received less attention from the city planner due to their modest size (such as Amande). This leverages the positive interplay between governance and grassroots action identified in Chapter 4 and strategically invests in the benefits most valued by the community. This support could take the form of increased funding, streamlined administrative processes, or formal integration into the city's educational outreach programs.
- **Adopt Gender-Responsive Management:** Garden associations and municipal planners should acknowledge that different members of the community experience the garden in different ways. The finding that women expressed significantly higher concern for pests and personal safety should inform practical management decisions.[1] This could translate into simple but meaningful measures like ensuring garden layouts are well-lit and pathways are clear to enhance feelings of security, or offering targeted workshops on organic pest management and the identification of beneficial insects to build confidence and address specific risk perceptions.

More broadly, for urban governance beyond Nantes, the FWS Sustainability Index offers a transformative tool for evidence-based decision-making. While its current comprehensive iteration provides a robust academic baseline, its future distillation into a streamlined Minimum Dataset will allow city planners and UFG managers to easily move from anecdotal success stories to an accessible, quantitative understanding of their green infrastructure. Furthermore, while the index deliberately avoids evaluating commercial profitability—as

these spaces operate outside the formal market—it functionally highlights the systemic economic vulnerabilities of cultivators, such as their dependence on purchased material inputs. This structural insight allows municipalities to benchmark performance across a city-wide network, diagnose specific resource frictions, and deploy targeted financial and infrastructural support where it is most needed, and to foster integrated policy by providing a common language and dataset that helps break down the administrative silos that often exist between municipal departments of parks, water, and waste management.

6.6 CONCLUDING REMARKS

This dissertation began with a simple premise: that to understand the sustainability of urban food gardens, we must first be willing to get our hands dirty. The dominant, high-level nexus frameworks, with their technocratic focus on large-scale resource flows, have consistently overlooked the most fundamental component of these vital urban ecosystems: the living soil beneath our feet. This theoretical oversight could result in practical consequences, leaving urban planners and communities without the tools they need to properly assess and manage these complex socio-ecological systems.

In response, this research has delivered two primary, interwoven contributions. First, it has proposed a novel conceptual model, the Food-Water-Soil nexus, that re-grounds sustainability assessment in the material reality and physiological dynamics of the urban edible landscapes. By placing soil at its rightful centre, the FWS nexus offers a more accurate and relevant paradigm for nature-based solutions. Second, it has translated this theory into a validated, practical tool—the FWS Sustainability Index. This index is more than just a list of

indicators; it is an instrument for adaptive management and evidence-based governance that is uniquely and powerfully informed by the voices, values, and concerns of the gardeners themselves.

Ultimately, this work argues for a more humble, grounded, and participatory science of urban sustainability. It demonstrates that by listening carefully to communities (e.g. Nantes Dialogue Citoyen), and by paying close attention to the foundational ecological processes that support them, we can develop more effective, resilient, and equitable strategies for greening our cities. The path to a sustainable urban future is not built solely on grand plans and abstract models; it is also cultivated, plot by plot, through the nurturing of the soil and, in doing so, the cultivation of the human and ecological capital upon which true urban resilience depend.

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8 APPENDIX

8.1 APPENDIX 1 – SUPPLEMENT MATERIALS FOR CHAPTER 2

Table A.1.1 Scales of analysis of reviewed papers

Scale of Analysis	Methodological Cluster	Number of Studies	References (Author, Year)
1. Plot & Building	Quantitative Sustainability Assessment	4	Dorr et al., 2017; Meng et al., 2023; Sanjuan-Delmás et al., 2018; Carrasco-Astudillo et al., 2024
	Systems & Nexus Modeling	5	Huang & Chang, 2021; Jans-Singh et al., 2021; Johnson et al., 2015; Piezer et al., 2019; Holt et al., 2017
	Empirical & Field-Based Studies	3	Grard et al., 2018; Taylor, 2020; Wright et al., 2021
2. Community & Neighborhood	Spatial Planning & Optimization	5	Cumo et al., 2025; Pedro et al., 2021; Smith et al., 2021; Zhang et al., 2022; Zheng et al., 2025
	Systems & Nexus Modeling	1	Valencia, Hossain, & Chang, 2022
	Socio-Ecological & Community Assessment	3	Kirby et al., 2021; Lowan-Trudeau et al., 2020; Siegner, Acey, & Sowerwine, 2020
	Empirical & Field-Based Studies	2	Caputo et al., 2023; Jha et al., 2023

Scale of Analysis	Methodological Cluster	Number of Studies	References (Author, Year)
3. City & Regional	Spatial Planning & Optimization	8	Fanfani et al., 2022; Lin et al., 2025; Liu, Lin, & Chiueh, 2022; Lucertini & Di Giustino, 2021; M. Susana & Geneletti, 2023; Ustaoglu et al., 2021; Zambrano-Prado et al., 2021; Small et al., 2023
	Systems & Nexus Modeling	6	Elkamel et al., 2023; Gondhalekar & Ramsauer, 2017; Goodarzi et al., 2022; Pueyo-Ros et al., 2024; Valencia, Zhang, & Chang, 2022; Weidner & Yang, 2020
	Socio-Ecological & Community Assessment	2	Nie, Kiminami, & Yagi, 2024; Valencia, Qiu, & Chang, 2022
	Empirical & Field-Based Studies	4	Chen et al., 2023; Dennis & James, 2017; Mulier et al., 2022; Sylla et al., 2020
4. Conceptual / Multi-Scale	Quantitative Sustainability Assessment	5	Imam et al., 2025; McDougall et al., 2019; Stone et al., 2021; Toboso-Chavero et al., 2019; Zhen et al., 2020
	Spatial Planning & Optimization	3	Camacho-Caballero et al., 2024; Kafle et al., 2023; Toboso-Chavero et al., 2023
	Socio-Ecological & Community Assessment	5	Babaei et al., 2024; Caputo et al., 2021; Kong et al., 2025; Rodríguez González et al., 2023; Toboso-Chavero et al., 2021
	Empirical & Field-Based Studies	1	Dorr et al., 2023

Scale of Analysis	Methodological Cluster	Number of Studies	References (Author, Year)
Total		**58**	

Table A.1.2 Common indicators used in integrated assessment for UFGs

Methodological Cluster	Indicator Category	Specific Input Parameter / Indicator	Frequency (Count of Papers)
Quantitative Sustainability Assessment	Resource Inputs (Material & Energy)	Infrastructure Materials (steel, plastic, wood, concrete)	10
		Substrate & Grow Media (compost, potting soil, etc.)	8
		Fertilizers & Soil Amendments (synthetic, organic, NPK)	8
		Water (tap water, irrigation)	7
		Energy (electricity, fuel, diesel)	7
		Pesticides & Herbicides	5
		Packaging Materials	2
		Other Inputs (seeds, earthworms)	2
	Economic Inputs	Operational Costs (labor, water, energy)	4
		Capital Costs (infrastructure, machinery)	3
		Land Rent / Value	2
	System & Production Parameters	Crop Type & Yield Data	9
		Life Cycle Stages (production, transport, waste)	8
		Food Waste Ratios	2

Methodological Cluster	Indicator Category	Specific Input Parameter / Indicator	Frequency (Count of Papers)
Spatial Planning & Optimization	Spatial & Geographic Data	Land Use / Land Cover (vacant land, green areas, etc.)	18
		Building Data (footprints, rooftop area, height)	14
		Infrastructure Networks (roads, public transit)	11
		Environmental Data (slope, elevation, aspect, hydrology)	9
		Climate Data (solar radiation, temperature, precipitation)	8
		Proximity to Features (markets, community spaces)	8
		Soil Properties (depth, drainage, capability class)	5
	Socio-Economic & Demographic Data	Population Data (density, age structure)	12
		Economic Indicators (income, unemployment)	10
		Health & Vulnerability Indicators (food deserts, heat vulnerability)	9
		Social Indicators (minority population, education level)	7
	Policy & Planning Scenarios	Land-Use Scenarios	7
		Siting Criteria (from stakeholders/literature)	6
		Development Goals & Constraints	4
		Budget / Resource Constraints	2
Systems & Nexus Modeling	Resource Flow & Consumption Data	Water Demand & Supply Data	11
		Energy Demand & Supply Data	11

Methodological Cluster	Indicator Category	Specific Input Parameter / Indicator	Frequency (Count of Papers)
		Food Demand & Supply Data	10
		Organic Waste Generation Rates	5
	System Design & Operational Parameters	Technology Specifications (PV efficiency, tank capacity)	8
		UA System Parameters (farm area, greenhouse setpoints)	7
		Agent Attributes (for ABM: income, preferences)	2
	External Drivers & Scenarios	Climate Change Projections (RCPs)	6
		Policy Scenarios	5
		Economic Scenarios (price inflation)	2
	Biophysical & Ecological Models	Plant Growth Models	3
		Evapotranspiration (ET) Models	2
		Hydrological Models (runoff, infiltration)	2
Socio-Ecological & Community Assessment	Participant & Community Demographics	Socio-Economic Data (age, income, education)	10
		Gardener Experience & Skill Level	3
	Social & Institutional Factors	Participant Motivations	5
		Stakeholder Perceptions & Preferences (AHP/Delphi)	5
		Governance Structures	3
		Social Networks & Cohesion	2
	Livelihood Capitals	Human Capital (knowledge, skills)	2
		Social Capital (networks, trust)	2

Methodological Cluster	Indicator Category	Specific Input Parameter / Indicator	Frequency (Count of Papers)
		Financial Capital (income, savings)	2
		Physical & Natural Capital (tools, land access)	2
	UA Site Characteristics	Site Typology (community garden, allotment, etc.)	8
		Food Distribution Model (self-consumption, sales)	4
		Management Practices (organic, conventional)	3
Empirical & Field-Based Studies	Resource Inputs (Measured)	Water Consumption (irrigation volume)	7
		Soil Amendments (compost, fertilizer application rates)	6
		Energy Use (fuel for machinery)	2
	Biophysical Site Characteristics	Site & Cultivated Area (m^2)	9
		Soil Quality Metrics (%OM, pH, CEC, nutrients)	5
		Floral & Vegetative Diversity (richness, abundance)	4
		Landscape Context (% impervious surface)	2
	Management Practices	Tillage System	2
		Crop Diversity & Polyculture Design	2
	Human Activity (Measured)	Labor Hours	4
		Volunteer Journeys (transport)	2

8.2 APPENDIX 2 – SUPPLEMENT MATERIALS FOR CHAPTER 4

Table A.2.1. Summary of the gardener demographics and gardening intensity

Category	Age	Daily_time	Day_week
25-34	1	0	0
35-54	7	0	0
55-64	21	0	0
65+	25	0	0
1-2hr	0	8	0
2-3hr	0	21	0
<1hr	0	3	0
>3hr	0	22	0
1-2 days per week	0	0	3
3-5days perweek	0	0	31
Everyday	0	0	20

Table A.2.2. Summary of waiting time to acquire an urban garden plot (year)

Garden	**Mean**	**Median**	**SD**	**IQR**
Overal	1,87	1,5	1,34	2
AC	1,5	1,5		
AM	1,18	1		
BR	2,17	2,5		
CR	1,86	1,5		
EG	2,2	2		

Table A.2.3. Results of Inferential Tests for Differences in Gardening Behavior by Gender and Age

Comparison	**statistic**	**p.value**	**estimate**	**method**
Gender vs Days/Week	347			
Gender vs Hours/Visit	370			
Age vs Days/Week	28341,18141	0,563889615	-0,080281357	Spearman's rank correlation rho
Age vs Hours/Visit	23581,55797	0,466789825	0,101141301	Spearman's rank correlation rho

Table A.2.4. Percentage, Median, and Interquartile Distribution of Perceived Importance of Ecosystem Services

Ecosystem service	Not important (%)	Slightly important (%)	Moderately important (%)	Highly important (%)	***Median***	***IQR***
Food Provision	0,0	7,4	38,9	53,7	4	1
Medicinal & Aromatic	0,0	13,0	51,9	35,2	3	1
Physical Health	0,0	11,1	25,9	63,0	4	1
Biodiversity	1,9	11,1	35,2	51,9	4	1
Soil Conservation	5,6	9,3	20,4	64,8	4	1
Education	0,0	3,7	22,2	74,1	4	0,75
Water Regulation	0,0	5,6	24,1	70,4	4	1
Social Cohesion	1,9	11,1	31,5	55,6	4	1
Air Quality	16,7	7,4	35,2	40,7	3	1
Mental Health	3,7	3,7	25,9	66,7	4	1

Note: Reponses were coded into a Likert scale system, with 1 = not important; 2 = slightly important, 3 = moderately important, 4 = highly importannt.

Table A.2.5. Percentage, Median, and Interquartile Distribution of Perceived Concern for Ecosystem Disservices

Ecosystem disservice	Not concerned (%)	Low concern (%)	Moderate concern (%)	High concern (%)	***Median***	***IQR***
Food Contamination	22,2	24,1	25,9	27,8	3	2
Green Waste	55,6	11,1	5,6	27,8	1	3
Water Consumption	3,7	9,3	25,9	61,1	4	1
Water Pollution	44,4	7,4	11,1	37,0	2	3
Soil Pollution	37,0	9,3	9,3	44,4	3	3
Air Pollution	53,7	20,4	11,1	14,8	1	1,75
Allergies	51,9	5,6	24,1	18,5	1	2
Maintenance Cost	46,3	22,2	25,9	5,6	2	2
Pest/Insect Bites	38,9	18,5	18,5	24,1	2	2
Fear of Wilderness	59,3	14,8	22,2	3,7	1	1,75
Unpleasant Odor	66,7	14,8	13,0	5,6	1	1

Note: Reponses were coded into a Likert scale system, with 1 = not concerned; 2 = low concern, 3 = moderate concern, 4 = high concern.

Table A.2.6. Kruskal-Wallis H Test Results for Differences in Perceptions Across Garden Sites

Item	statistic	df	p	Effect Size (η^2)	magnitude
Ecosystem disservices					
Air Pollution	3,302134	4	0,509	-0,01424	small
Allergies	2,594788	4	0,628	-0,02868	small
Pet/Insect Bites	9,02966	4	0,0604	0,102646	moderate
Food Contamination	7,867545	4	0,0966	0,078929	moderate
Maintenance Cost	5,197139	4	0,268	0,024431	small
Fear of Wilderness	1,334525	4	0,855	-0,0544	small
Unpleasant Odor	0,960967	4	0,916	-0,06202	moderate
Soil Pollution	3,053896	4	0,549	-0,01931	small
Water Consumption	2,511272	4	0,643	-0,03038	small
Water Pollution	2,912591	4	0,573	-0,02219	small
Green Waste	0,391347	4	0,983	-0,07365	moderate
Ecosystem services					
Air Quality	0,828225	4	0,935	-0,06473	moderate
Biodiversity	4,100938	4	0,393	0,00206	small
Education	3,416873	4	0,491	-0,0119	small
Food Provision	2,433323	4	0,657	-0,03197	small
Medicinal & Aromatic	1,028371	4	0,905	-0,06065	moderate
Mental Health	2,025075	4	0,731	-0,0403	small
Physical Health	2,372224	4	0,668	-0,03322	small
Social Cohesion	2,441561	4	0,655	-0,0318	small
Soil Conservation	1,375358	4	0,848	-0,05356	small
Water Regulation	1,679924	4	0,794	-0,04735	small

Table A.2.7. Mann-Whitney U Test Results for Differences in Perceptions Between Genders

Item	statistic	p	Effect Size (η^2)	magnitude
Ecosystem disservices				
Air Pollution	405,5	0,437	0,107164	small
Allergies	452,5	0,0966	0,227429	small
Pet/Insect Bites	512,5	0,00739	0,365762	moderate
Food Contaimination	408	0,436	0,107112	small
Maint	356,5	0,897	0,018916	small
Fear of Wilderness	500	0,00782	0,363267	moderate
Unpleasant Odor	438,5	0,125	0,210024	small
Soil Pollution	374,5	0,852	0,026672	small
Water Consumption	438	0,143	0,200799	small
Water Pollution	414	0,355	0,127025	small
Green Waste	352	0,824	0,031492	small
Ecosystem services				
Air Quality	398	0,537	0,085188	small
Biodiversity	504	0,0075	0,36513	moderate
Education	378	0,759	0,043206	small
Food Provision	376,5	0,815	0,033212	small
Medicinal & Aromatic	601,5	5,51E-06	0,619721	large
Mental Health	423	0,222	0,167767	small
Physical Health	354	0,848	0,027538	small
Social Cohesion	310	0,299	0,142568	small
Soil Conservation	360	0,943	0,011117	small
Water Regulation	537	0,000184	0,510401	large

Table A.2.8. Polychoric Correlation Matrix of Ecosystem Service and Disservice Perception

Item	Food Provision	Medicinal & Aromatic	Physical Health	Biodiversity	Soil Conservation	Education	Water Regulation	Social Cohesion	Air Quality	Mental Health	Food Contamination	Green Waste	Water Consumption	Water Pollution	Soil Pollution	Air Pollution	Allergies	Maintenance Cost	Pest/Insect Bites	Fear of Wilderness	Unpleasant Odor
Food Provision	1																				
Medicinal & Aromatic	-0,16	1																			
Physical Health	0,39	-0,10	1																		
Biodiversity	-0,06	0,41	0,15	1																	
Soil Conservation	-0,02	-0,06	0,19	0,74	1																
Education	-0,13	0,16	0,28	0,58	0,45	1															
Water Regulation	0,24	0,23	0,09	0,55	0,37	-0,04	1														
Social Cohesion	-0,07	-0,17	0,42	0,19	0,47	0,14	0,25	1													
Air Quality	-0,08	-0,06	0,28	0,38	0,51	0,50	0,45	0,49	1												
Mental Health	0,42	0,08	0,54	0,44	0,41	-0,03	0,53	0,51	0,17	1											
Food Contamination	0,03	0,06	0,11	0,27	0,11	0,03	0,20	-0,20	-0,08	0,30	1										
Green Waste	-0,33	0,04	-0,01	0,45	0,10	0,13	0,28	-0,10	0,02	0,06	0,34	1									
Water Consumption	-0,17	0,04	0,10	0,43	0,21	0,15	0,17	-0,05	0,16	0,07	0,32	0,53	1								
Water Pollution	-0,42	0,00	-0,20	0,44	0,34	0,32	-0,09	0,02	0,04	0,17	0,37	0,30	0,27	1							
Soil Pollution	-0,31	-0,12	-0,20	0,17	0,15	0,04	-0,10	-0,11	0,07	0,14	0,46	0,20	0,30	0,87	1						
Air Pollution	-0,24	0,11	-0,03	0,43	0,13	0,50	0,21	-0,25	0,27	0,07	0,27	0,46	0,08	0,57	0,51	1					
Allergies	-0,32	0,32	-0,17	0,29	-0,08	-0,20	0,28	-0,13	-0,13	0,24	0,25	0,66	0,44	0,42	0,46	0,44	1				
Maintenance Cost	0,05	-0,06	0,10	0,23	0,22	0,16	0,31	0,20	0,22	0,23	0,28	0,37	0,10	0,04	-0,01	0,25	0,37	1			
Pest/Insect Bites	0,03	0,20	0,21	0,45	0,15	0,19	0,42	0,04	0,23	0,41	0,33	0,24	0,32	0,34	0,30	0,46	0,46	0,40	1		
Fear of Wilderness	0,12	0,38	0,00	0,46	0,06	0,05	0,43	0,07	-0,12	0,39	0,43	0,36	0,47	0,22	0,12	0,11	0,56	0,52	0,48	1	
Unpleasant Odor	-0,02	0,39	-0,32	0,25	-0,12	-0,05	0,31	-0,30	-0,06	0,10	0,34	0,37	0,23	0,14	0,26	0,42	0,65	0,48	0,40	0,60	1

Table A.2.9. Rotated Factor Loading Matrix (Pattern Matrix) from Exploratory Factor Analysis

ES and EDS	PA1	PA2	PA3	PA4
Ecosystem services				
Food Provision	-0,03132	-0,22458	-0,31712	0,513779
Medicinal & Aromatic	0,467272	0,163671	-0,23258	-0,18472
Physical Health	-0,2041	0,182587	-0,10358	0,534477
Biodiversity	0,365923	0,752903	0,035312	0,100842
Soil Conservation	-0,17505	0,661263	0,134565	0,282299
Education	-0,09584	0,794697	0,034759	-0,20373
Water Regulation	0,453009	0,300298	-0,26935	0,367909
Social Cohesion	-0,31196	0,321361	-0,04241	0,485238
Air Quality	-0,16139	0,684776	-0,0503	0,115309
Mental Health	0,109541	0,007436	0,122486	0,906891
Ecosystem disservices				
Food Contamination	0,337213	-0,08376	0,341731	0,233502
Green Waste	0,533951	0,210838	0,155838	-0,12513
Water Consumptiom	0,349586	0,177419	0,184422	0,026925
Water Pollution	0,005055	0,184046	0,906046	-0,02592
Soil Pollution	0,004813	-0,11005	0,979985	0,069452
Air Pollution	0,316397	0,377747	0,364794	-0,21528
Allergies	0,761998	-0,11557	0,282318	-0,01817
Maintenance Cost	0,443525	0,166818	-0,08113	0,194021
Pet/Insect Bites	0,449553	0,185841	0,161417	0,259838
Fear of Wilderness	0,761435	-0,01111	-0,05825	0,26811
Unpleasant Odor	0,847633	-0,07124	-0,02761	-0,11731

Table A.2.10. Variance Explained by the Extracted Factors

Statistic	SS loadings	Proportion Var	Cumulative Var	Proportion Explained	Cumulative Proportion
PA1	3,833806	0,182562	0,182562	0,326341	0,326341
PA2	2,931666	0,139603	0,322165	0,249549	0,575891
PA3	2,637462	0,125593	0,447759	0,224506	0,800397
PA4	2,344908	0,111662	0,559421	0,199603	1

Table A.2.11. Inter-Factor Correlation Matrix (Phi Matrix)

Factor	PA1	PA2	PA3	PA4
PA1	1	0,12136	0,263191	0,123024
PA2	0,12136	1	0,179014	0,241945
PA3	0,263191	0,179014	1	-0,0491
PA4	0,123024	0,241945	-0,0491	1

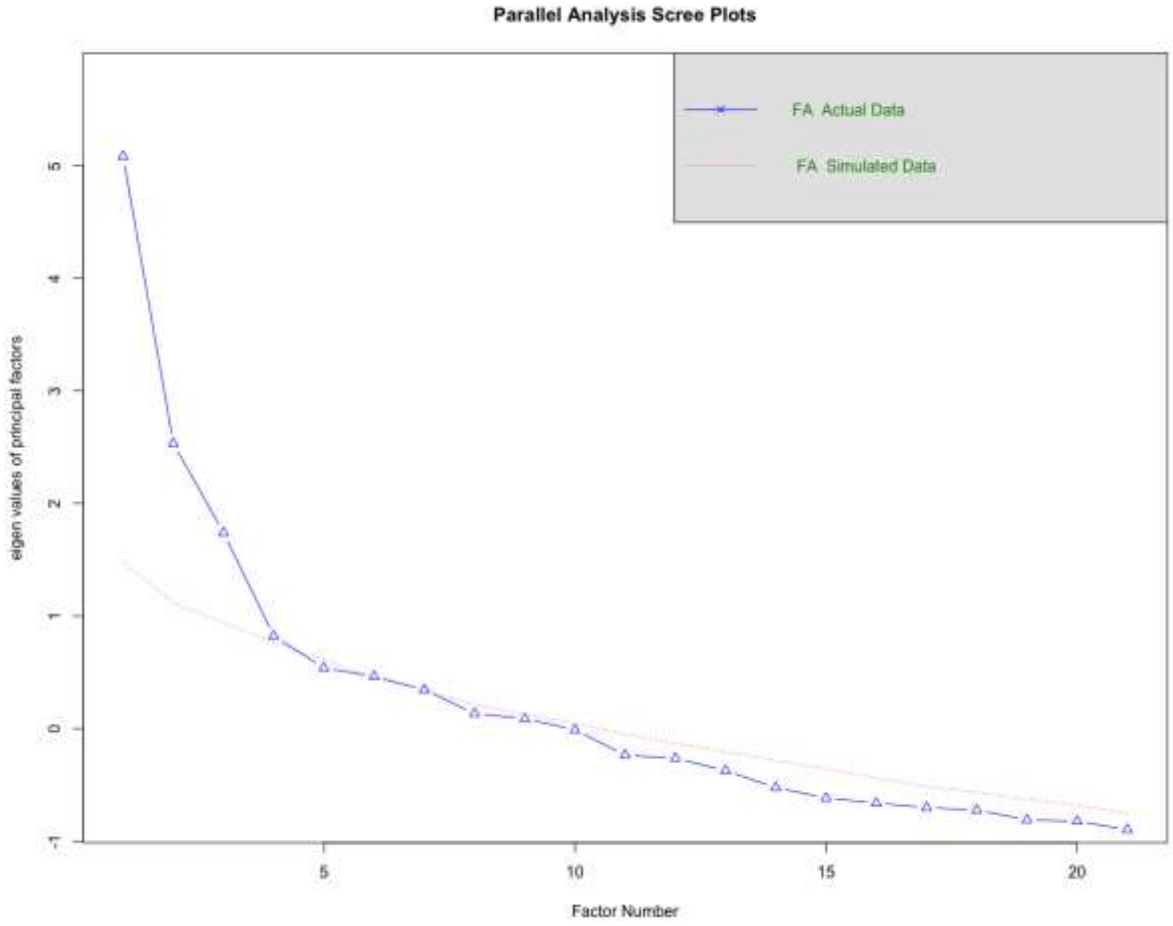

Figure B.2.1. Scree Plots of Result from Parallel Analysis

8.3 APPENDIX 3 – SUPPLEMENT MATERIALS FOR CHAPTER 5

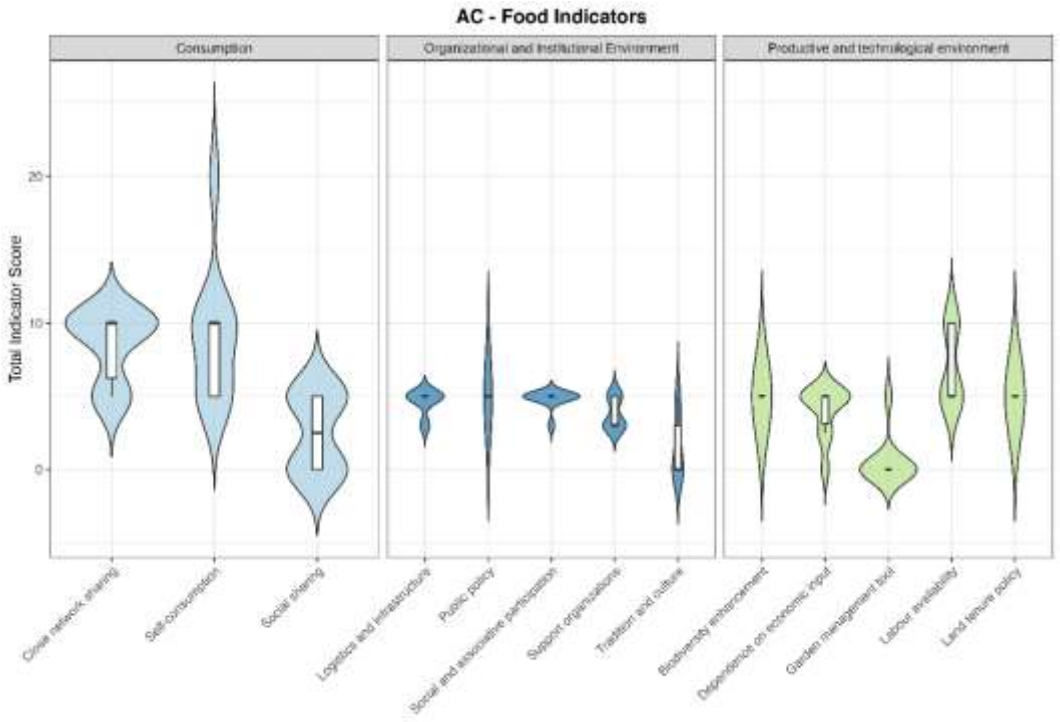

Figure A.3.1 Score distribution of Food indicators in Angle Chaillou

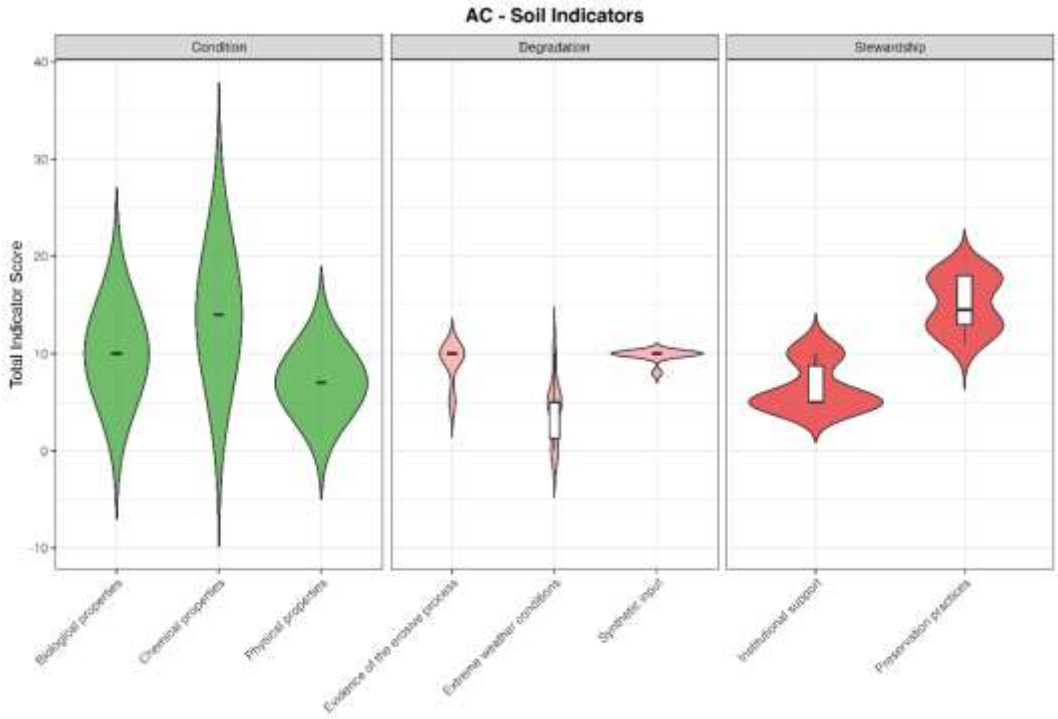

Figure A.3.2 Score distribution of Soil indicators in Angle Chaillou garden

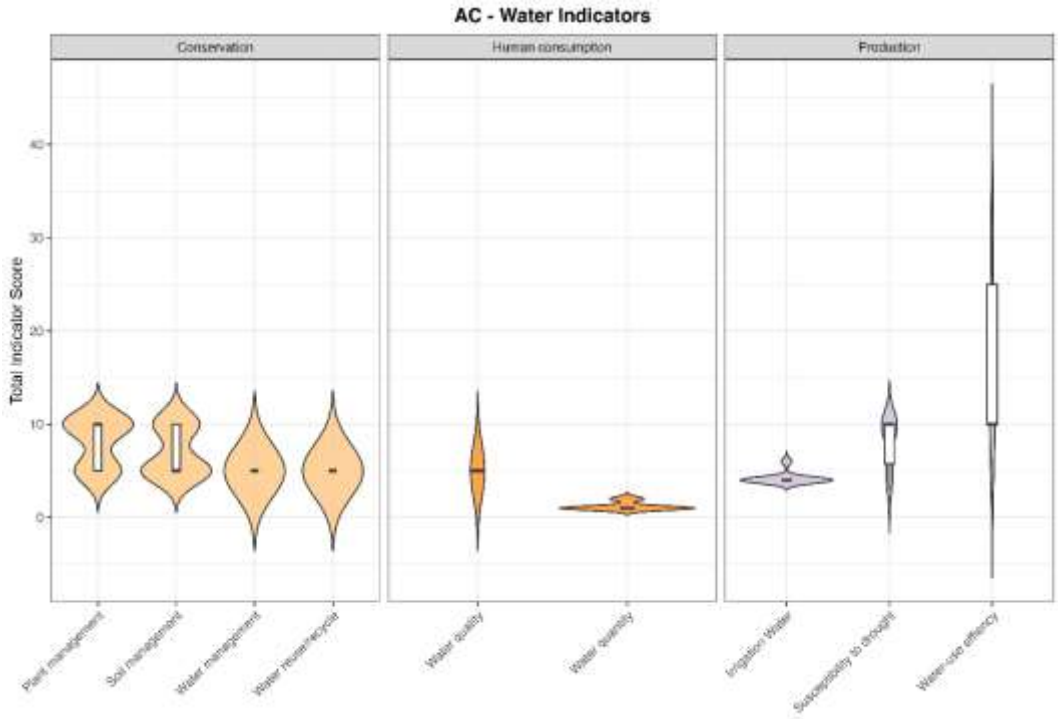

Figure A.3.3 Score distribution of Water indicators in Angle Chaillou garden

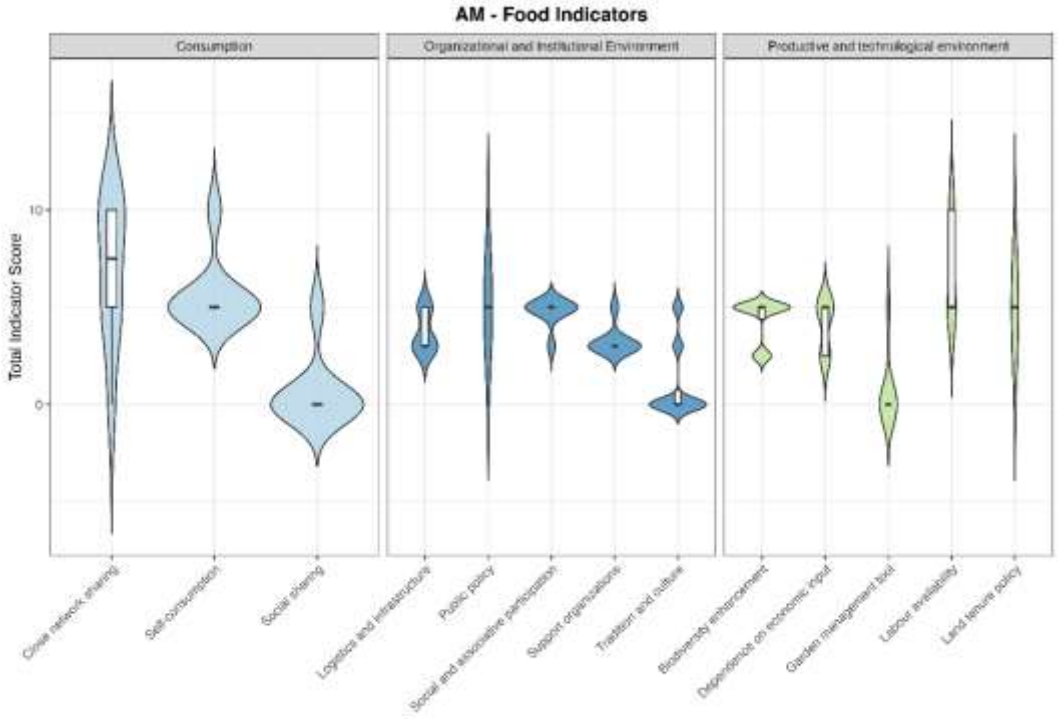

Figure A.3.4 Score distribution of Food indicators in Amande garden

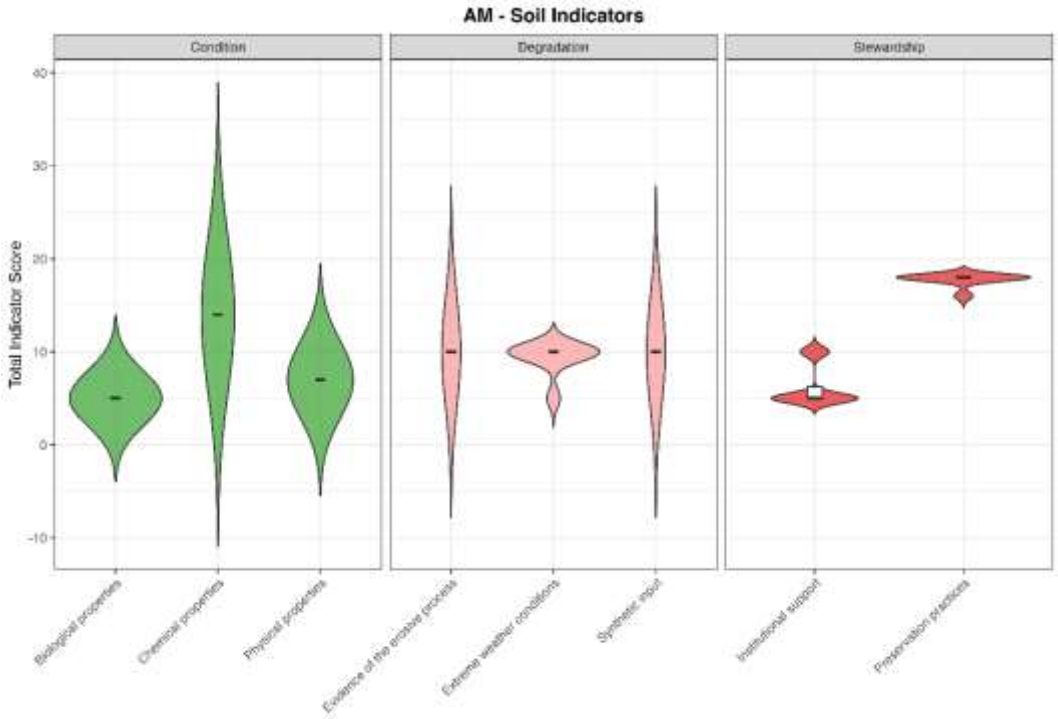

Figure A.3.5 Score distribution of Soil indicators in Amande garden

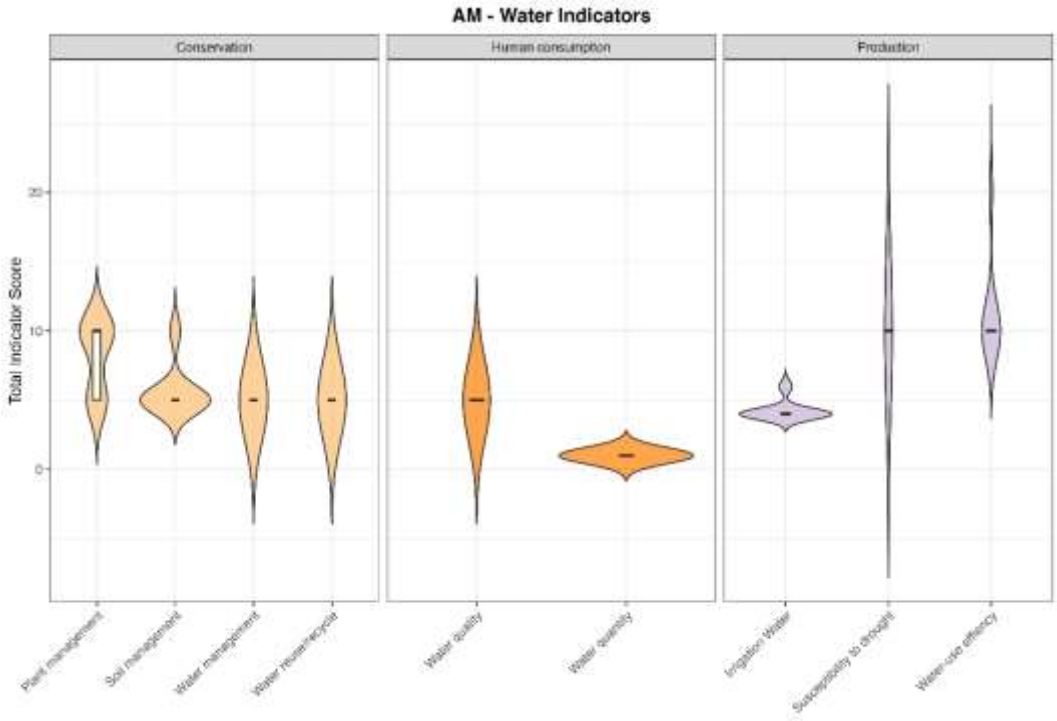

Figure A.3.6 Score distribution of Water indicators in Amande garden

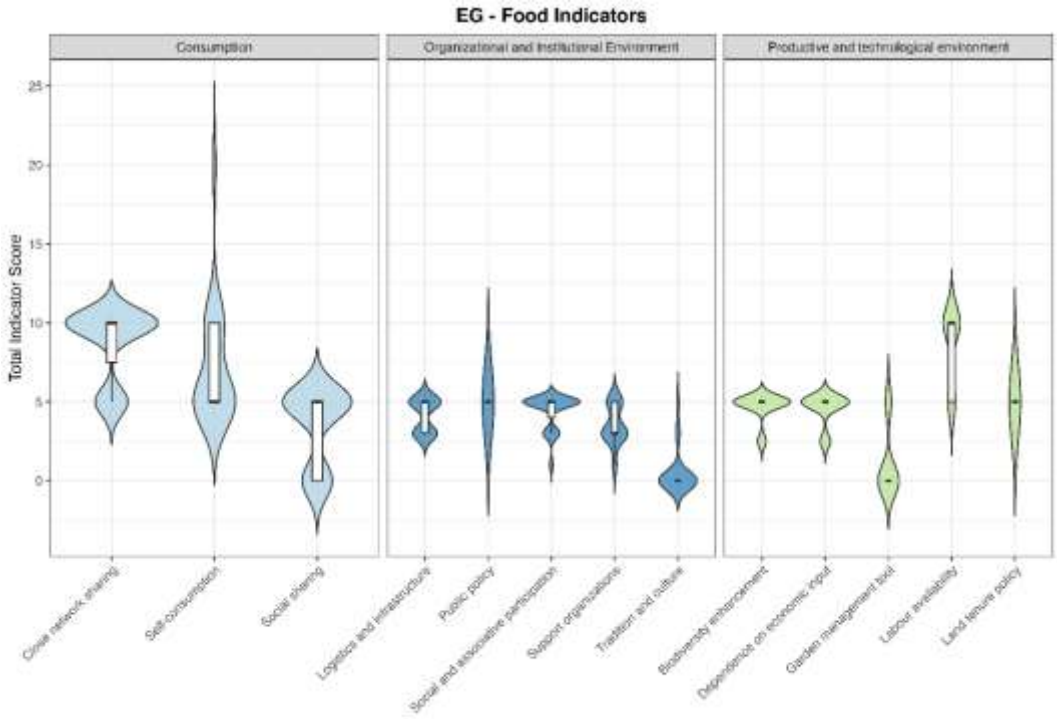

Figure A.3.7 Score distribution of Food indicators in Eglantiers garden

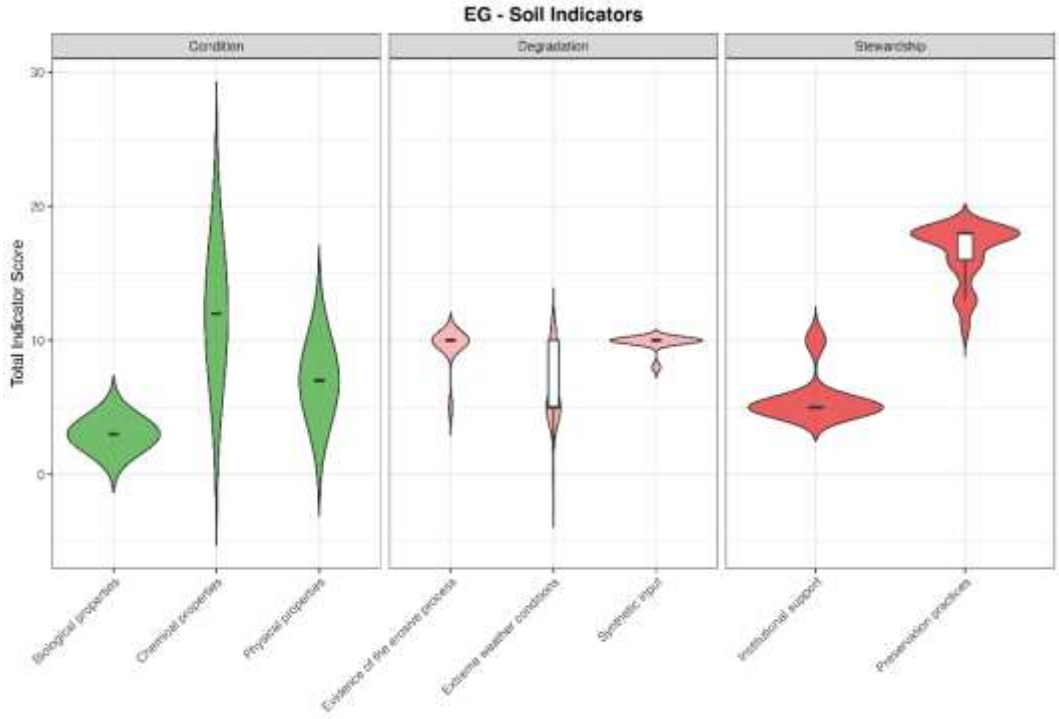

Figure A.3.8 Score distribution of Soil indicators in Eglantiers garden

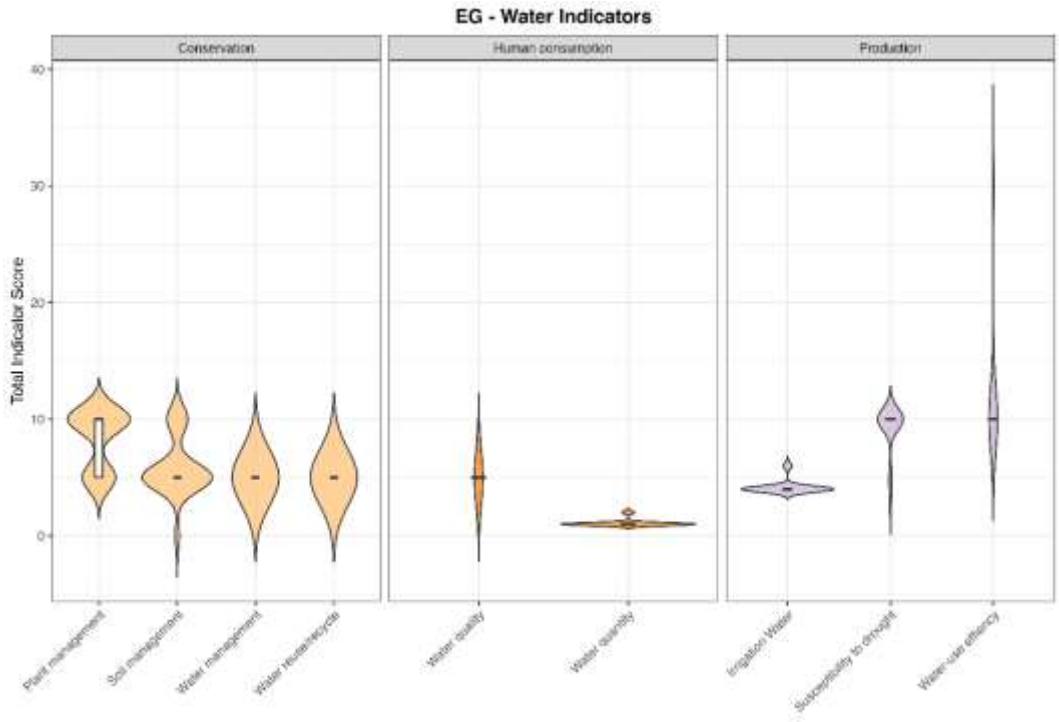

Figure A.3.9 Score distribution of Water indicators in Eglantiers garden

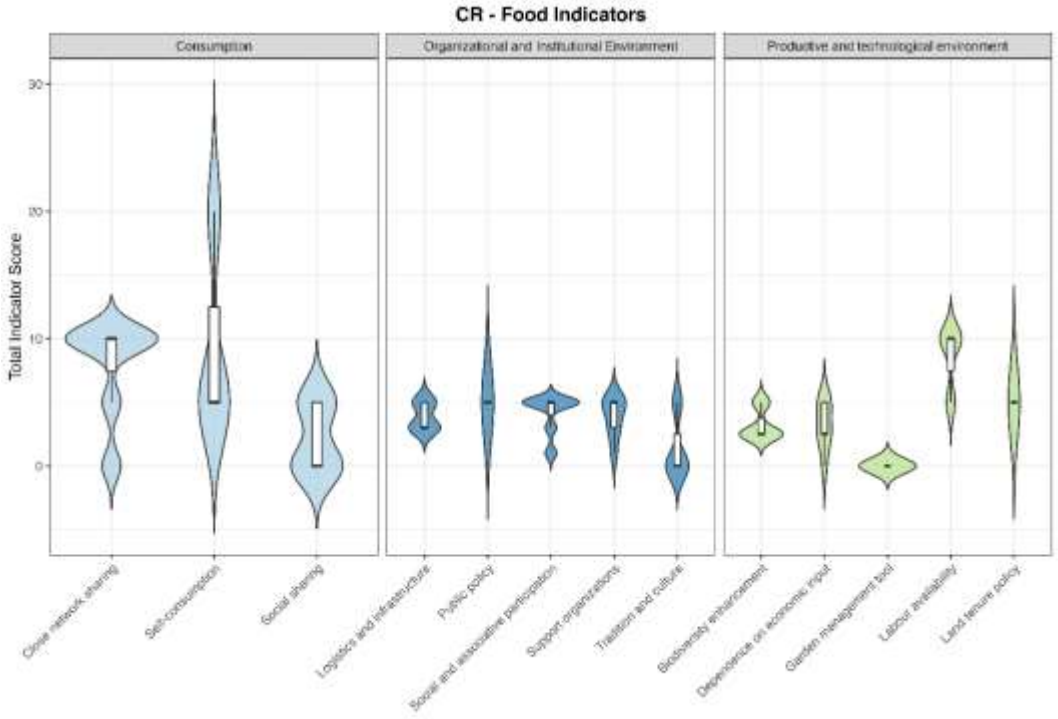

Figure A.3.10 Score distribution of Food indicators in Cressonière garden

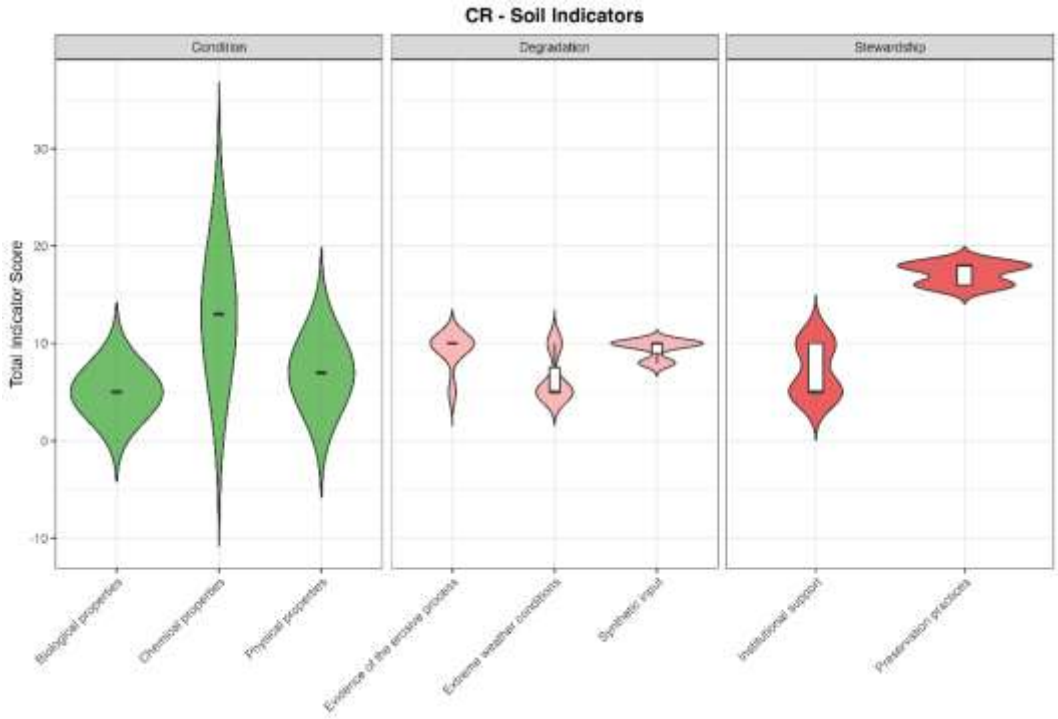

Figure A.3.11 Score distribution of Soil indicators in Cressonière garden

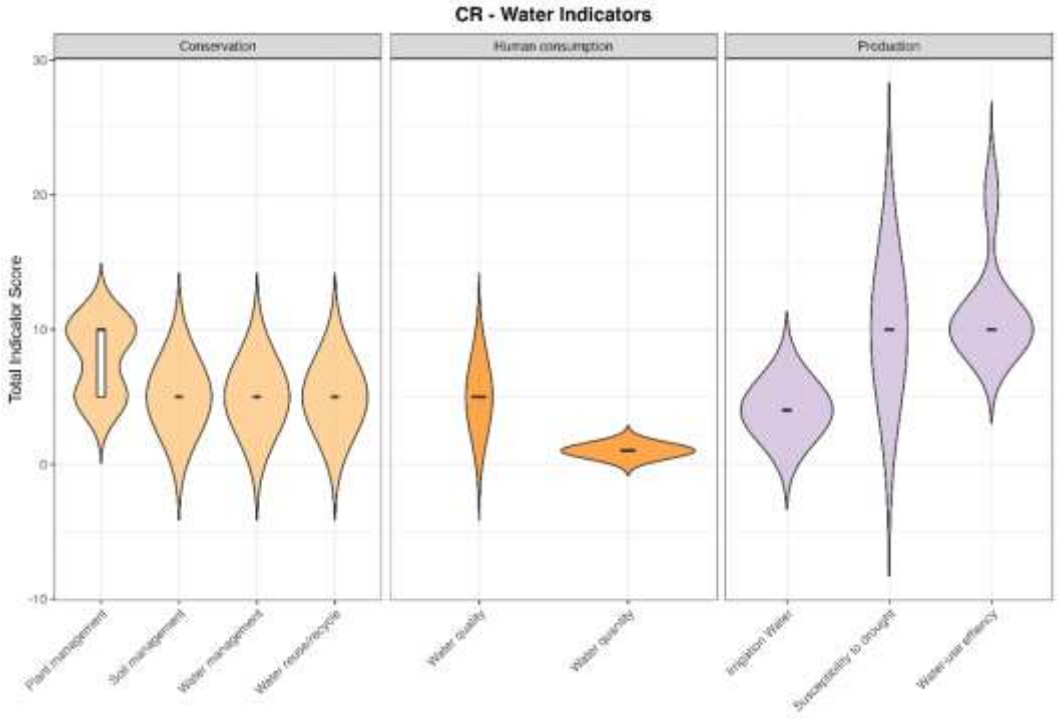

Figure A.3.12 Score distribution of Water indicators in Cressonière

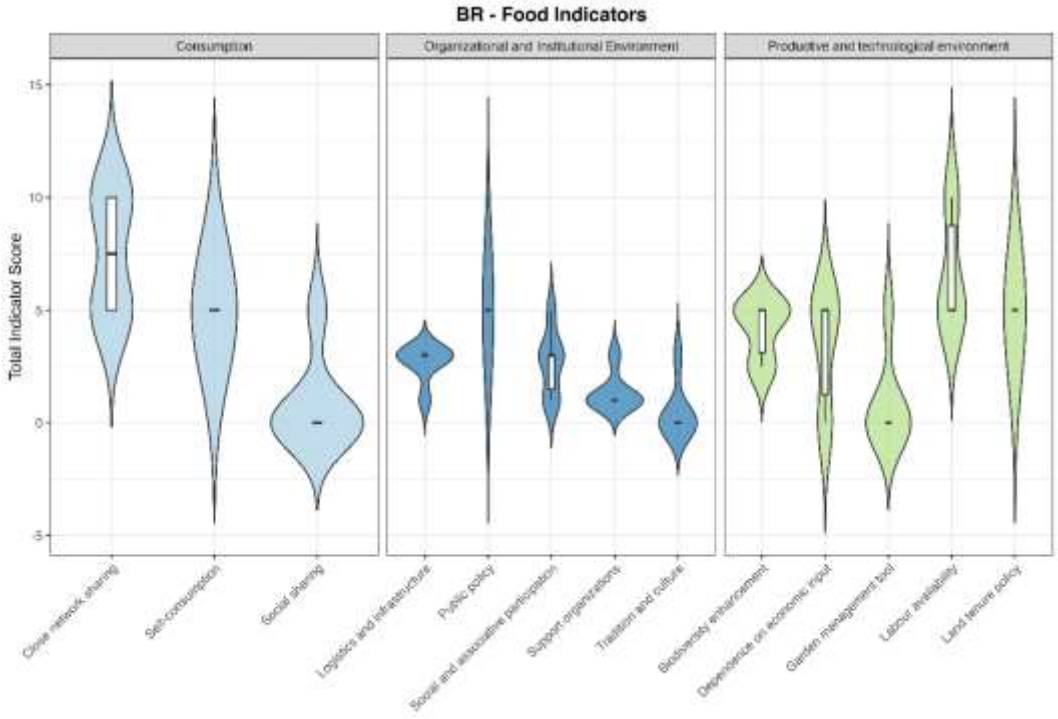

Figure A.3.13 Score distribution of Food indicators in Bruyères garden

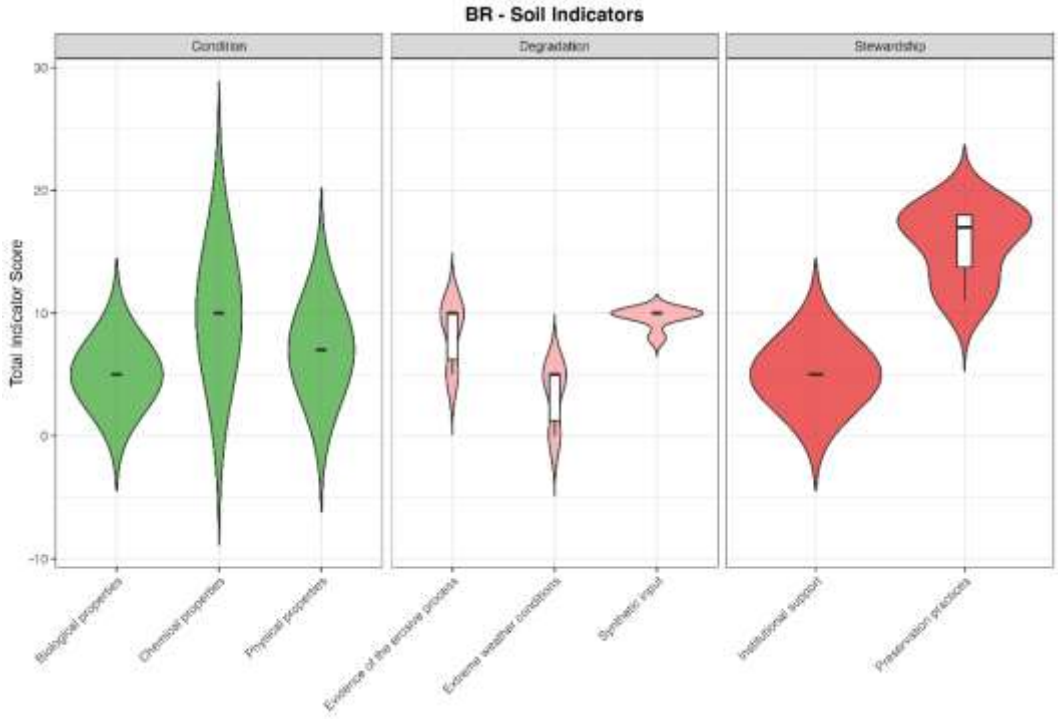

Figure A.3.14 Score distribution of Soil indicators in Bruyères garden

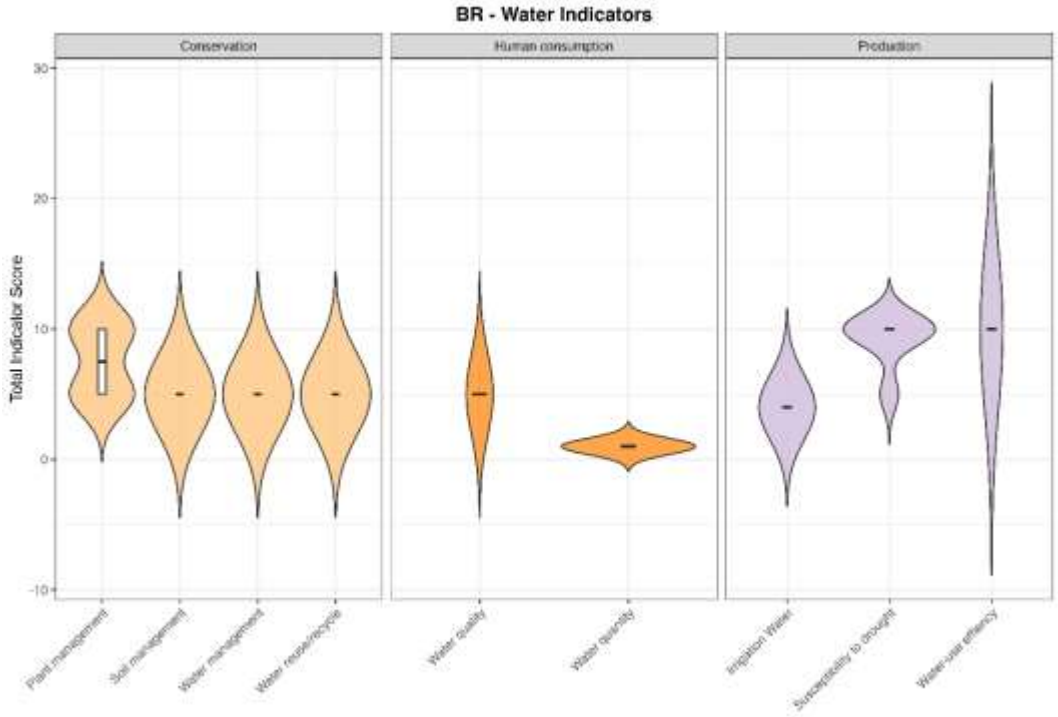

Figure A.3.15 Score distribution of Water indicators in Bruyères

Table B.3.1 FWS axis scores (0-100) for each of the all gardens

Garden_ID	Food	Soil	Water
AC	61.3	75.4	59.5
AM	51.8	79.4	55.3
BR	45.5	64.0	51.7
CR	57.6	74.4	54.3
EG	60.7	69.9	55.8

Table B.3.2 Test results from the Kruskal-Wallis analysis for all sample

axis	kw_statistic	kw_p.value	Significant_p_lt_0.05
Food	17.9401992	0.00126775	TRUE
Soil	25.3253891	4.3271E-05	TRUE
Water	3.19111499	0.52636722	FALSE

Table B.3.3 Test results from the Friedman analysis for all gardens

garden_id	friedman_p.value	Significant_p_lt_0.05
AC	0.020241911	TRUE
AM	0.001503439	TRUE
BR	0.069483451	FALSE
CR	0.018315639	TRUE
EG	1.39374E-06	TRUE

Table B.3.4 Dunn's post-hoc test results for comparing the difference between gardens

axis	comparison	p.adjusted
Food	BR - EG	0.00266117
Food	AC - BR	0.0066419
Food	AM - EG	0.0453806
Food	AC - AM	0.0809796
Food	BR - CR	0.19376833
Food	AM - BR	1
Food	AC - CR	1
Food	AM - CR	1
Food	AC - EG	1
Food	CR - EG	1
Soil	AM - BR	0.00010146
Soil	AM - EG	0.00059572
Soil	AC - BR	0.01181707
Soil	BR - CR	0.03642762
Soil	AC - EG	0.12599236
Soil	CR - EG	0.37076657
Soil	BR - EG	0.57591063
Soil	AM - CR	0.59102639
Soil	AC - AM	0.61506764
Soil	AC - CR	1

Table B.3.5 Paired Wilcoxon post-hoc test results for comparing the difference between axes of each garden

garden_id	group1	group2	p.adj	p.adj.signif
AC	Food	Soil	0.032	*
AC	Soil	Water	0.043	*
AC	Food	Water	0.915	ns
AM	Food	Soil	0.023	*
AM	Soil	Water	0.041	*
AM	Food	Water	0.699	ns
CR	Soil	Water	0.067	ns
CR	Food	Soil	0.094	ns
CR	Food	Water	1	ns
EG	Food	Soil	0.000275	***
EG	Soil	Water	0.000396	***
EG	Food	Water	0.046	*

Table B.3.6. Statistics summary for each axis indicator across all 54 plots

Axis	Scope	Indicator	Mean _Score	Median _Score	Std _Dev	Min_ Score	Q1 _Score	Q3 _Score	Max _Score
Food	Consumption	Close network sharing	8.15	10	2.80	0	5	10	10
Food	Consumption	Self-consumption	7.31	5	4.20	5	5	10	20
Food	Consumption	Social sharing	2.41	0	2.52	0	0	5	5
Food	Org. & Insti. Envi.	Logistics and infrastructure	3.96	4	1.08	1	3	5	5
Food	Org. & Insti. Envi	Public policy	5.00	5	0.00	5	5	5	5
Food	Org. & Insti. Envi	Social and associative participation	4.30	5	1.24	1	3	5	5
Food	Org. & Insti. Envi	Support organizations	3.33	3	1.33	1	3	5	5
Food	Org. & Insti. Envi	Tradition and culture	0.89	0	1.74	0	0	0	5
Food	Prod. & techn. Envi	Biodiversity enhancement	4.44	5	1.05	2.5	5	5	5
Food	Prod. & techn. Envi	Dependence on economic input	4.07	5	1.56	0	2.5	5	5
Food	Prod. & techn. Envi	Garden management tool	0.74	0	1.79	0	0	0	5
Food	Prod. & techn. Envi	Labour availability	7.78	10	2.51	5	5	10	10
Food	Prod. & techn. Envi	Land tenure policy	5.00	5	0.00	5	5	5	5
Soil	Condition	Biological properties	5.07	5	2.54	3	3	5	10
Soil	Condition	Chemical properties	12.57	12	1.27	10	12	14	14
Soil	Condition	Physical properties	7.00	7	0.00	7	7	7	7
Soil	Degradation	Evidence of the erosive process	9.35	10	1.70	5	10	10	10
Soil	Degradation	Extreme weather conditions	6.02	5	3.13	0	5	10	10
Soil	Degradation	Synthetic input	9.78	10	0.63	8	10	10	10
Soil	Stewardship	Institutional support	6.02	5	2.03	5	5	5	10
Soil	Stewardship	Preservation practices	16.44	18	2.24	11	16	18	18
Water	Conservation	Plant management	8.06	10	2.46	5	5	10	10
Water	Conservation	Soil management	5.83	5	2.12	0	5	5	10
Water	Conservation	Water management	5.00	5	0.00	5	5	5	5
Water	Conservation	Water reuse/recycle	5.00	5	0.00	5	5	5	5
Water	Human consumption	Water quality	5.00	5	0.00	5	5	5	5
Water	Human consumption	Water quantity	1.07	1	0.26	1	1	1	2
Water	Production	Irrigation Water	4.15	4	0.53	4	4	4	6
Water	Production	Susceptibility to drought	9.24	10	1.92	3	10	10	10
Water	Production	Water-use efficiency	12.41	10	6.12	10	10	10	30

Table A5. Detailed statistics for each indicator, broken down by each of the 5 garden

Table B.3.7. Statistics summary for each axis indicator across all 54 plots

Garden_ID	Axis	Scope	Indicator	Mean_Score	Median_Score	Std_Dev	Min_Score	Q1_Score	Q3_Score	Max_Score	N_Samples
AC	Food	Consumption	Close network sharing	8.5	10.0	2.4	5	6.25	10	10	10
AC	Food	Consumption	Self-consumption	9.0	10.0	4.6	5	5	10	20	10
AC	Food	Consumption	Social sharing	2.5	2.5	2.6	0	0	5	5	10
AC	Food	Org. & Insti. Envi.	Logistics and infrastructure	4.6	5.0	0.8	3	5	5	5	10
AC	Food	Org. & Insti. Envi.	Public policy	5.0	5.0	0.0	5	5	5	5	10
AC	Food	Org. & Insti. Envi.	Social and associative participation	4.8	5.0	0.6	3	5	5	5	10
AC	Food	Org. & Insti. Envi.	Support organizations	3.8	3.0	1.0	3	3	5	5	10
AC	Food	Org. & Insti. Envi.	Tradition and culture	1.6	0.0	2.2	0	0	3	5	10
AC	Food	Prod. & techn. Envi	Biodiversity enhancement	5.0	5.0	0.0	5	5	5	5	10
AC	Food	Prod. & techn. Envi	Dependence on economic input	4.0	5.0	1.7	0	3.125	5	5	10
AC	Food	Prod. & techn. Envi	Garden management tool	0.5	0.0	1.6	0	0	0	5	10
AC	Food	Prod. & techn. Envi	Labour availability	7.0	5.0	2.6	5	5	10	10	10
AC	Food	Prod. & techn. Envi	Land tenure policy	5.0	5.0	0.0	5	5	5	5	10
AC	Soil	Condition	Biological properties	10.0	10.0	0.0	10	10	10	10	10
AC	Soil	Condition	Chemical properties	14.0	14.0	0.0	14	14	14	14	10
AC	Soil	Condition	Physical properties	7.0	7.0	0.0	7	7	7	7	10
AC	Soil	Degradation	Evidence of the erosive process	9.0	10.0	2.1	5	10	10	10	10
AC	Soil	Degradation	Extreme weather conditions	4.0	5.0	3.2	0	1.25	5	10	10
AC	Soil	Degradation	Synthetic input	9.8	10.0	0.6	8	10	10	10	10
AC	Soil	Stewardship	Institutional support	6.5	5.0	2.4	5	5	8.75	10	10
AC	Soil	Stewardship	Preservation practices	15.1	14.5	2.8	11	13	18	18	10
AC	Water	Conservation	Plant management	8.0	10.0	2.6	5	5	10	10	10
AC	Water	Conservation	Soil management	7.0	5.0	2.6	5	5	10	10	10
AC	Water	Conservation	Water management	5.0	5.0	0.0	5	5	5	5	10
AC	Water	Conservation	Water reuse/recycle	5.0	5.0	0.0	5	5	5	5	10
AC	Water	Human consumption	Water quality	5.0	5.0	0.0	5	5	5	5	10
AC	Water	Human consumption	Water quantity	1.2	1.0	0.4	1	1	1	2	10
AC	Water	Production	Irrigation Water	4.2	4.0	0.6	4	4	4	6	10
AC	Water	Production	Susceptibility to drought	8.1	10.0	2.7	3	5.75	10	10	10
AC	Water	Production	Water-use effiency	16.0	10.0	9.7	10	10	25	30	10
AM	Food	Consumption	Close network sharing	6.9	7.5	3.7	0	5	10	10	8
AM	Food	Consumption	Self-consumption	5.6	5.0	1.8	5	5	5	10	8
AM	Food	Consumption	Social sharing	0.6	0.0	1.8	0	0	0	5	8

Garden_ID	Axis	Scope	Indicator	Mean_Score	Median_Score	Std_Dev	Min_Score	Q1_Score	Q3_Score	Max_Score	N_Samples
AM	Food	Org. & Insti. Envi.	Logistics and infrastructure	3.8	3.0	1.0	3	3	5	5	8
AM	Food	Org. & Insti. Envi.	Public policy	5.0	5.0	0.0	5	5	5	5	8
AM	Food	Org. & Insti. Envi.	Social and associative participation	4.8	5.0	0.7	3	5	5	5	8
AM	Food	Org. & Insti. Envi.	Support organizations	3.3	3.0	0.7	3	3	3	5	8
AM	Food	Org. & Insti. Envi.	Tradition and culture	1.0	0.0	1.9	0	0	0.75	5	8
AM	Food	Prod. & techn. Envi	Biodiversity enhancement	4.4	5.0	1.2	2.5	4.375	5	5	8
AM	Food	Prod. & techn. Envi	Dependence on economic input	4.1	5.0	1.3	2.5	2.5	5	5	8
AM	Food	Prod. & techn. Envi	Garden management tool	0.6	0.0	1.8	0	0	0	5	8
AM	Food	Prod. & techn. Envi	Labour availability	6.9	5.0	2.6	5	5	10	10	8
AM	Food	Prod. & techn. Envi	Land tenure policy	5.0	5.0	0.0	5	5	5	5	8
AM	Soil	Condition	Biological properties	5.0	5.0	0.0	5	5	5	5	8
AM	Soil	Condition	Chemical properties	14.0	14.0	0.0	14	14	14	14	8
AM	Soil	Condition	Physical properties	7.0	7.0	0.0	7	7	7	7	8
AM	Soil	Degradation	Evidence of the erosive process	10.0	10.0	0.0	10	10	10	10	8
AM	Soil	Degradation	Extreme weather conditions	9.4	10.0	1.8	5	10	10	10	8
AM	Soil	Degradation	Synthetic input	10.0	10.0	0.0	10	10	10	10	8
AM	Soil	Stewardship	Institutional support	6.3	5.0	2.3	5	5	6.25	10	8
AM	Soil	Stewardship	Preservation practices	17.8	18.0	0.7	16	18	18	18	8
AM	Water	Conservation	Plant management	8.1	10.0	2.6	5	5	10	10	8
AM	Water	Conservation	Soil management	5.6	5.0	1.8	5	5	5	10	8
AM	Water	Conservation	Water management	5.0	5.0	0.0	5	5	5	5	8
AM	Water	Conservation	Water reuse/recycle	5.0	5.0	0.0	5	5	5	5	8
AM	Water	Human consumption	Water quality	5.0	5.0	0.0	5	5	5	5	8
AM	Water	Human consumption	Water quantity	1.0	1.0	0.0	1	1	1	1	8
AM	Water	Production	Irrigation Water	4.3	4.0	0.7	4	4	4	6	8
AM	Water	Production	Susceptibility to drought	10.0	10.0	0.0	10	10	10	10	8
AM	Water	Production	Water-use effiency	11.3	10.0	3.5	10	10	10	20	8
BR	Food	Consumption	Close network sharing	7.5	7.5	2.7	5	5	10	10	6
BR	Food	Consumption	Self-consumption	5.0	5.0	0.0	5	5	5	5	6
BR	Food	Consumption	Social sharing	0.8	0.0	2.0	0	0	0	5	6
BR	Food	Org. & Insti. Envi.	Logistics and infrastructure	2.7	3.0	0.8	1	3	3	3	6
BR	Food	Org. & Insti. Envi.	Public policy	5.0	5.0	0.0	5	5	5	5	6
BR	Food	Org. & Insti. Envi.	Social and associative participation	2.7	3.0	1.5	1	1.5	3	5	6
BR	Food	Org. & Insti. Envi.	Support organizations	1.3	1.0	0.8	1	1	1	3	6
BR	Food	Org. & Insti. Envi.	Tradition and culture	0.5	0.0	1.2	0	0	0	3	6
BR	Food	Prod. & techn. Envi	Biodiversity enhancement	4.2	5.0	1.3	2.5	3.125	5	5	6
BR	Food	Prod. & techn. Envi	Dependence on economic input	3.3	5.0	2.6	0	1.25	5	5	6

Garden_ID	Axis	Scope	Indicator	Mean_Score	Median_Score	Std_Dev	Min_Score	Q1_Score	Q3_Score	Max_Score	N_Samples
BR	Food	Prod. & techn. Envi	Garden management tool	0.8	0.0	2.0	0	0	0	5	6
BR	Food	Prod. & techn. Envi	Labour availability	6.7	5.0	2.6	5	5	8.75	10	6
BR	Food	Prod. & techn. Envi	Land tenure policy	5.0	5.0	0.0	5	5	5	5	6
BR	Soil	Condition	Biological properties	5.0	5.0	0.0	5	5	5	5	6
BR	Soil	Condition	Chemical properties	10.0	10.0	0.0	10	10	10	10	6
BR	Soil	Condition	Physical properties	7.0	7.0	0.0	7	7	7	7	6
BR	Soil	Degradation	Evidence of the erosive process	8.3	10.0	2.6	5	6.25	10	10	6
BR	Soil	Degradation	Extreme weather conditions	3.3	5.0	2.6	0	1.25	5	5	6
BR	Soil	Degradation	Synthetic input	9.7	10.0	0.8	8	10	10	10	6
BR	Soil	Stewardship	Institutional support	5.0	5.0	0.0	5	5	5	5	6
BR	Soil	Stewardship	Preservation practices	15.7	17.0	3.0	11	13.75	18	18	6
BR	Water	Conservation	Plant management	7.5	7.5	2.7	5	5	10	10	6
BR	Water	Conservation	Soil management	5.0	5.0	0.0	5	5	5	5	6
BR	Water	Conservation	Water management	5.0	5.0	0.0	5	5	5	5	6
BR	Water	Conservation	Water reuse/recycle	5.0	5.0	0.0	5	5	5	5	6
BR	Water	Human consumption	Water quality	5.0	5.0	0.0	5	5	5	5	6
BR	Water	Human consumption	Water quantity	1.0	1.0	0.0	1	1	1	1	6
BR	Water	Production	Irrigation Water	4.0	4.0	0.0	4	4	4	4	6
BR	Water	Production	Susceptibility to drought	9.2	10.0	2.0	5	10	10	10	6
BR	Water	Production	Water-use effiency	10.0	10.0	0.0	10	10	10	10	6
CR	Food	Consumption	Close network sharing	7.9	10.0	3.9	0	7.5	10	10	7
CR	Food	Consumption	Self-consumption	9.3	5.0	7.3	5	5	12.5	20	7
CR	Food	Consumption	Social sharing	2.1	0.0	2.7	0	0	5	5	7
CR	Food	Org. & Insti. Envi.	Logistics and infrastructure	3.9	3.0	1.1	3	3	5	5	7
CR	Food	Org. & Insti. Envi.	Public policy	5.0	5.0	0.0	5	5	5	5	7
CR	Food	Org. & Insti. Envi.	Social and associative participation	4.1	5.0	1.6	1	4	5	5	7
CR	Food	Org. & Insti. Envi.	Support organizations	3.9	5.0	1.6	1	3	5	5	7
CR	Food	Org. & Insti. Envi.	Tradition and culture	1.4	0.0	2.4	0	0	2.5	5	7
CR	Food	Prod. & techn. Envi	Biodiversity enhancement	3.2	2.5	1.2	2.5	2.5	3.75	5	7
CR	Food	Prod. & techn. Envi	Dependence on economic input	3.2	2.5	1.9	0	2.5	5	5	7
CR	Food	Prod. & techn. Envi	Garden management tool	0.0	0.0	0.0	0	0	0	0	7
CR	Food	Prod. & techn. Envi	Labour availability	8.6	10.0	2.4	5	7.5	10	10	7
CR	Food	Prod. & techn. Envi	Land tenure policy	5.0	5.0	0.0	5	5	5	5	7
CR	Soil	Condition	Biological properties	5.0	5.0	0.0	5	5	5	5	7
CR	Soil	Condition	Chemical properties	13.0	13.0	0.0	13	13	13	13	7
CR	Soil	Condition	Physical properties	7.0	7.0	0.0	7	7	7	7	7
CR	Soil	Degradation	Evidence of the erosive process	9.3	10.0	1.9	5	10	10	10	7
CR	Soil	Degradation	Extreme weather conditions	6.4	5.0	2.4	5	5	7.5	10	7

Garden_ID	Axis	Scope	Indicator	Mean_Score	Median_Score	Std_Dev	Min_Score	Q1_Score	Q3_Score	Max_Score	N_Samples
CR	Soil	Degradation	Synthetic input	9.4	10.0	1.0	8	9	10	10	7
CR	Soil	Stewardship	Institutional support	7.1	5.0	2.7	5	5	10	10	7
CR	Soil	Stewardship	Preservation practices	17.1	18.0	1.1	16	16	18	18	7
CR	Water	Conservation	Plant management	7.9	10.0	2.7	5	5	10	10	7
CR	Water	Conservation	Soil management	5.0	5.0	0.0	5	5	5	5	7
CR	Water	Conservation	Water management	5.0	5.0	0.0	5	5	5	5	7
CR	Water	Conservation	Water reuse/recycle	5.0	5.0	0.0	5	5	5	5	7
CR	Water	Human consumption	Water quality	5.0	5.0	0.0	5	5	5	5	7
CR	Water	Human consumption	Water quantity	1.0	1.0	0.0	1	1	1	1	7
CR	Water	Production	Irrigation Water	4.0	4.0	0.0	4	4	4	4	7
CR	Water	Production	Susceptibility to drought	10.0	10.0	0.0	10	10	10	10	7
CR	Water	Production	Water-use effiency	11.4	10.0	3.8	10	10	10	20	7
EG	Food	Consumption	Close network sharing	8.7	10.0	2.2	5	7.5	10	10	23
EG	Food	Consumption	Self-consumption	7.2	5.0	3.6	5	5	10	20	23
EG	Food	Consumption	Social sharing	3.5	5.0	2.4	0	0	5	5	23
EG	Food	Org. & Insti. Envi.	Logistics and infrastructure	4.1	5.0	1.0	3	3	5	5	23
EG	Food	Org. & Insti. Envi.	Public policy	5.0	5.0	0.0	5	5	5	5	23
EG	Food	Org. & Insti. Envi.	Social and associative participation	4.4	5.0	1.1	1	4	5	5	23
EG	Food	Org. & Insti. Envi.	Support organizations	3.5	3.0	1.2	1	3	5	5	23
EG	Food	Org. & Insti. Envi.	Tradition and culture	0.5	0.0	1.3	0	0	0	5	23
EG	Food	Prod. & techn. Envi	Biodiversity enhancement	4.7	5.0	0.9	2.5	5	5	5	23
EG	Food	Prod. & techn. Envi	Dependence on economic input	4.6	5.0	1.0	2.5	5	5	5	23
EG	Food	Prod. & techn. Envi	Garden management tool	1.1	0.0	2.1	0	0	0	5	23
EG	Food	Prod. & techn. Envi	Labour availability	8.5	10.0	2.4	5	5	10	10	23
EG	Food	Prod. & techn. Envi	Land tenure policy	5.0	5.0	0.0	5	5	5	5	23
EG	Soil	Condition	Biological properties	3.0	3.0	0.0	3	3	3	3	23
EG	Soil	Condition	Chemical properties	12.0	12.0	0.0	12	12	12	12	23
EG	Soil	Condition	Physical properties	7.0	7.0	0.0	7	7	7	7	23
EG	Soil	Degradation	Evidence of the erosive process	9.6	10.0	1.4	5	10	10	10	23
EG	Soil	Degradation	Extreme weather conditions	6.3	5.0	2.7	0	5	10	10	23
EG	Soil	Degradation	Synthetic input	9.8	10.0	0.6	8	10	10	10	23
EG	Soil	Stewardship	Institutional support	5.7	5.0	1.7	5	5	5	10	23
EG	Soil	Stewardship	Preservation practices	16.6	18.0	2.1	11	16	18	18	23
EG	Water	Conservation	Plant management	8.3	10.0	2.4	5	5	10	10	23
EG	Water	Conservation	Soil management	5.9	5.0	2.5	0	5	5	10	23
EG	Water	Conservation	Water management	5.0	5.0	0.0	5	5	5	5	23
EG	Water	Conservation	Water reuse/recycle	5.0	5.0	0.0	5	5	5	5	23

Garden_ID	Axis	Scope	Indicator	Mean_Score	Median_Score	Std_Dev	Min_Score	Q1_Score	Q3_Score	Max_Score	N_Samples
EG	Water	Human consumption	Water quality	5.0	5.0	0.0	5	5	5	5	23
EG	Water	Human consumption	Water quantity	1.1	1.0	0.3	1	1	1	2	23
EG	Water	Production	Irrigation Water	4.2	4.0	0.6	4	4	4	6	23
EG	Water	Production	Susceptibility to drought	9.3	10.0	2.0	3	10	10	10	23
EG	Water	Production	Water-use effiency	12.2	10.0	6.0	10	10	10	30	23

8.4 APPENDIX 4 – QUESTIONNAIRE FOR CHAPTER 4 & 5

Jardin: *Date de l'entretien*: *Taille de la parcelle:*

Nom du jardinier : *Sexe:*

Tranche d'âge: *Statut professionnel :*

Questions générales

1. Combien de temps vous a-t-il fallu pour obtenir l'attribution d'une parcelle ?
.....

3. Quel pourcentage de produits issus des jardins couvre votre consommation journalière? (80-90-100% etc)

.....
.....

4. Venez-vous du monde rural? Avez vous des compétences en jardinage, en culture avant de prendre le jardin?

☐ oui ☐ non

5. Combien d'heures par jour consacrez-vous au jardinage?

☐ moins d'une heure ☐ 1 - 2 heures ☐ 2 - 3 heures ☐ plus de 3 heures

6. Combien de fois allez-vous au jardin?

☐ tous les jours ☐ plusieurs fois par semaine ☐ une fois par semaine ☐ moins souvent

7. Quelle végétation (fruits et légumes) cultivez-vous dans le jardin ?
.....
.....
.....
.....

9. Qui consomme les produits du jardin ?

☐ famille exclusivement ☐ partager volontairement avec des amis/voisins ☐ autre

Si vous partagiez des légumes avec des amis ou des voisins, à quelle fréquence le faisiez-vous ?

☐ Non ☐ Occasionnellement ☐ Fréquemment

10. Quels types d'outils de gestion utilisez-vous pour le choix des légumes ou les dépenses du jardin ?

☐ Logiciel pour ordinateur/smartphone ☐ Livre/tableur pour la culture des légumes ☐ Je ne les utilise pas..

Services et disservices écosystémiques

11. Nous allons maintenant vous présenter une liste benefices des jardins urbains, et nous aimerions que vous les classiez en fonction de leur importance pour vous, allant de : "Ne me concerne pas", "Priorité basse", "Priorité moyenne" et "Priorité élevée".

	Ne me concerne pas	*Priorité basse*	*Priorité moyenne*	*Priorité élevée*
Production alimentaire				
Herbes médicinales/aromatiques et fleurs				
Le jardinage dans le cadre de l'exercice physique pour la santé				
Protéger et améliorer la biodiversité et la nature				
Protéger les sols et réduire leur érosion				
Améliorer les connaissances sur le jardinage et la nature				
Améliorer l'efficacité de l'utilisation de l'eau et la conservation de l'eau				
Renforcer les relations entre les résidents de la communauté				
Renforcer les relations entre les personnes âgées et les jeunes				
Réduire la dépendance alimentaire au marché et aux grandes surfaces				
Améliorer les conditions environnementales				

atmosphériques et climatiques dans la zone environnante.				
Améliorer les conditions économiques de la famille				
Amélioration de l'humeur par l'embellissement et l'amélioration esthétique				
Améliorer vos connaissances sur les plantes/insectes/animaux/la nature et les interactions entre eux				

12. Nous allons vous proposer une liste d'éléments qui peuvent être considérées comme des nuisances liées aux jardins. Pour chaque élément, pourriez-vous indiquer si cela vous pose problème ou non, en utilisant cette échelle : Pas de préoccupation, Préoccupation légère, Préoccupation modérée, Forte préoccupation.

	Pas de préoccupation	*Préoccupation légère*	*Préoccupation modérée*	*Forte préoccupation*
Végétaux contaminés (air, eau et sol contaminés)				
Déchets de jardinage				
Consommation d'eau				
Pollution de l'eau par les intrants chimiques				
Pollution des sols par les intrants chimiques				
Risque de pollution lié aux composés organiques volatils des plantes				

Allergies et maladies de la peau				
Coûts d'installation et de maintenance (frais de location, frais d'équipement, frais de graines pour les légumes et les herbes.)				
Piqûres d'insectes et de parasites				
Peur et risques liés à la nature sauvage				
Sons et odeurs désagréables				

SOIL & WATER RESOURCE

13. Quelle est l'origine de la terre de votre jardin ?

☐ sol local ☐ acheté en magasin ☐ mélange des deux ☐ autres.....

14. Travaillez-vous le sol avant les cultures (par exemple, labourage, décompactage)?

☐ oui ☐ non

15. A quelle fréquence travaillez-vous le sol ?

☐ moins d'une fois par an ☐ une fois par an ☐ 2 à 4 fois par an ☐ plus de 4 fois par an

16. Utilisez-vous des engrais ?

☐ non ☐ engrais organique (s) ☐ engrais inorganique (s)

17. Compostez-vous les déchets verts de votre jardin?

☐ oui ☐ non

18. Pratiquez-vous la gestion des sols?

☐ maintenir le sol couvert, ☐ ajouter de la matière organique, ☐ labour de conservation, ☐ ajouter du compost et du fumier, ☐ rotation des cultures, ☐ utiliser des cultures de couverture, ☐ éviter ou limiter l'utilisation de pesticides, ☐ préserver la biodiversité, cultures de couverture et paillage. ☐ auther ☐ non

19. Intervenez-vous sur la pente de votre jardin ?

☐ oui (degré d'inclinaison, le cas échéant) ☐ non

20. Remarquez-vous que le sol est érodé par le vent ?

☐ oui ☐ non ☐ incertain

21. Avez-vous remarqué que le sol s'est érodé ou a été emporté par de fortes pluies ?

☐ oui ☐ non ☐ incertain

22. Quelle est la fréquence des fortes pluies ? - (les fortes pluies sont celles où les gens remarquent le débordement)

☐ Jamais ☐ Rarement (une fois tous les 1 à 2 ans)☐ Fréquents (plusieurs fois par an)

23. Remarquez-vous si une pluie normale créé un débordement ?

☐ non ☐ Occasionnel ☐ Souvent

24. Y a-t-il une pénurie d'eau à tout moment de l'année en raison des conditions météorologiques ?

☐ Toutes les saisons ☐ En été ☐ Jamais

☐ Autre (année sèche/problème d'approvisionnement en eau)

25. Quelle est l'origine de l'eau utilisée pour l'irrigation ?

☐ eau de pluie ☐ eau du robinet ☐ puits ☐ autres.....

Supplémentaire : quelle est la source principale ?

26. Si vous utilisez l'eau du robinet, avez-vous un compteur d'eau pour le jardin ?

☐ oui ☐ non

27. Combien de fois par jour arrosez-vous votre jardin (y compris avec l'aide d'autres personnes) ?

☐ une fois ☐ deux fois ☐ plus de deux fois ☐ quelques fois par semaine ☐ Autres

.....

28. Savez-vous combien d'eau votre parcelle de jardin utilise chaque jour pour l'arrosage ?

---

29. L'eau répond-elle à vos besoins en matière de jardinage ? Quantité - à noter pour les différents types de sources d'eau (***Veuillez lire l'option à voix haute***)

☐ Ne répond pas ☐ Satisfaire à peine à la demande ☐ Satisfaire pleinement

30. Quelle est votre impression sur la qualité de l'eau pour le jardinage (pluie/robinet) ?

☐ Bonne ☐ Moyenne ☐ Mauvaise

Additional question for the garden association president/vice/secretary – skip for normal gardener

2. Pendant combien de temps pouvez-vous utiliser le terrain attribué ?
.....

31. Quelle est la source d'eau du jardin pour l'usage humain (lavage/nettoyage/boisson) ? Y a-t-il un mélange de sources d'eau ? (note : comme le robinet pour une chose et l'eau de pluie pour une autre)

☐ eau de pluie ☐ eau du robinet ☐ eau de puits ☐ autres.....

32. Que pensez-vous de la qualité de l'eau pour l'usage humain ?

☐ Bonne ☐ Moyenne ☐ Pauvre

39. Êtes-vous informé de toute analyse de la qualité de l'eau ?

☐ Non ☐ Oui

41. Recevez-vous des informations sur la gestion des sols (directives/exigences) de la part de la municipalité?

☐ Oui ☐ Non ☐ incertain

42. Connaissez-vous des politiques publiques qui soutiennent les activités de jardinage ?

☐ oui (nombre: .....) ☐ non

43 Dans quelle mesure pensez-vous que le soutien de la ville à l'association de jardinage est utile ?

☐ Peu utile ☐ Légèrement utile ☐ Très utile

Remarque

8.5 APPENDIX 5 – GENERAL INFORMATION OF STUDIED ALLOTMENT GARDENS

8.5.1 Eglantiers Allotment garden

Located in the northern sector of the city (Route de la Chapelle-sur-Erdre / Avenue des Églantiers), this site is one of the oldest family allotment gardens in the metropolis, established in 1982. Spanning approximately 2.3 hectares (92 plots), it functions as a hinge between dense urban fabric and the Bout des Landes Bruyères urban development zone (ZAC). In Nantes, the garden acts as a buffer zone between the A11 motorway and residential quarters. It contributes to the Nantes "Green Star," a radial network of greenways. The Jardin des Églantiers in Nantes is de jure public land but de facto private, as access is restricted to members.

After the discovery of natural soil contamination in 2012, a redevelopment program for the site was launched with expert gardeners and the City's Institute for Research in Science and Technology. The Églantiers family garden has thus become an experimental site included in the national research program on urban community gardens (JASSUR). Below are some image showing landscapes of the garden:


Nantes
Jardins familiaux des
Églantiers
Ouverture du portail
ALLONANTES
02 40 41 9000







8.5.2 Angle Chaillou Allotment Gardens

Angle Chaillou Allotment Gardens represents a historical layer of the city's agricultural past now repurposed for social and ecological resilience The garden has a total 58 plots, with the total surface at 14469 m2. Situated in the Nantes Nord district (11 Chemin de l'Angle Chaillou), the site is strategically positioned at the convergence of historical transit axes. Similar to the Églantiers site, gardens in Nantes Nord are subjects of concern within the Pollusols research program (OSUNA/CNRS). The historical proximity to industrial activities and heavy transit (A11 motorway) raises the probability of diffuse pollution by Trace Metallic Elements (TME), specifically lead (Pb) and arsenic (As).

The garden is adjacent to new residential developments (e.g., the Habitat44 projects), illustrating the tension between the ZAN (Zéro Artificialisation Nette) objectives and the need for housing. These gardens are often perceived as "land reserves" by developers, leading to a constant political struggle to validate their social and ecological value over potential real estate yield.

As Nantes Nord undergoes urban renewal, these gardens risk becoming "green enclaves" that increase the property value of surrounding new builds, potentially displacing the lower-income populations the gardens were originally designed to support. Bellow are some pictures of the garden landscape.





8.5.3 Amande Alloment garden

The Jardin de l’Amande (Almond Garden) is situated in the Nantes Nord district, specifically framed by Boulevard René-Cassin and Rue des Roches (18-24 Rue des Roches). It occupies a central position within the Parc de l’Amande, an area formerly characterized by rural undergrowth and traditional agriculture before being absorbed by the rapid urbanization of the Boissière and Bout des Landes sectors.

While the wider park dates back to the primary development of the northern urban clusters, the contemporary iteration of the allotment gardens was formalized through the Service des Espaces Verts (SEVE) of Nantes. It has recently undergone a major transformation as part of the European Urbinat project (2023–2024). The specific allotment garden association (Association Les Jardins de l'Amande) manages approximately 4,754 square meters, with 21 individual plots.

From its conception, the site integrated sustainable water management technologies, specifically rainwater harvesting systems attached to each garden shed—a proactive response to the increasing hydric stress in urban soil profiles. In 2023, the garden was

integrated into a "Green Loop" (Boucle Verte). This represents a shift in urban philosophy: the garden is no longer an isolated social utility but a node in a "Healthy Corridor" designed to combat urban heat islands and sedentary lifestyles.

Bellow are some pictures of the garden





8.5.4 Bruyères Allоment garden

The Jardin des Bruyères (Bruyères Allotment Gardens) situated in the Nantes Nord sector, specifically in the Bout des Landes neighborhood. The current iteration of the gardens was inaugurated in 2014, encompasses approximately 11,300 square meters, facilitates 30 individual plots. A critical feature is the inclusion of a collective plot (managed by the Centre Socio-Culturel Accoord Bout des Landes), which serves as a laboratory for social pedagogy and shared agricultural labor, rather than purely private subsistence.

The Jardin des Bruyères is not an isolate but a functional component of the Trame Verte et Bleue (Green and Blue Framework), with a specific "soft pathway" (cheminement doux) connects the Jardin des Bruyères to the Jardin des Églantiers. This physical continuity allows for the migration of urban biodiversity (corridors) while providing a pedestrian loop for residents.

It serves as a pivotal link between the dense residential blocks and the peripheral green belts. It is adjectant to Eglantiers Allotment garden. The site is positioned within a strategic "Healthy Corridor" (as defined by the European URBiNAT project), aimed at revitalizing social housing estates through nature-based solutions. As part of the URBiNAT Healthy Corridor, the garden acts as a

thermal regulator (mitigating the urban heat island effect) and a hydrological sponge, capturing runoff from the surrounding impervious social housing surfaces.

8.5.5 Cressonnière Allotment Garden

The Jardin de la Cressonnière is a modest but ecologically significant allotment garden located in the Nantes Nord district, nestled within the Coulée verte des Renards (Foxes' Green Corridor) in northern Nantes. It is situated in a naturally humid sector of the city, which historically dictated its land use. The "coulée verte" acts as a vital pedestrian and biological link between the urban density of the northern quarters and the more open landscapes of the Erdre valley. The garden was formalized as part of the city's broader initiative to re-establish "jardins familiaux" (allotment gardens) within the ecological frameworks of the metropolitan area.

The site is one of the smaller allotments in the city, consisting of only 8 cultivated plots. Since its inception, the garden has been managed according to the principles of "jardinage au naturel" (natural gardening). This strictly prohibits the use of chemical fertilizers and pesticides, aligning with the city’s environmental charter for the Coulée verte. Access is primarily via "soft" transit (walking or

cycling) through the green corridor paths. While the surrounding paths are public, the 8 plots are fenced and restricted to the members of the local garden association.

Like other gardens in the northern sector, the site's historical proximity to industrial development and road runoff (from the Boulevard Robert Schuman corridor) necessitates ongoing soil monitoring, although its position within a protected green corridor provides some buffer against direct atmospheric particulates

Below are some pictures of the Cressonnière garden





8.6 APPENDIX 6 – PHOTO COLLECTED DURING INTERVIEWING AND SAMPLING PROCESS



Figure A.5.1 Example of urban gardens in Thu Dau Mot -1



Figure A.5.2 Example of urban gardens in Thu Dau Mot - 2



Figure A.5.3 Data collection from urban gardens in Thu Dau Mot



Figure A.5.4. Garden participation at AC with our intern



Figure A.5.5. Photo from interview process of urban garden plot at EG - 1




quand on sème
c'est
pour la Vie

Figure A.5.6. Photo from interview process of urban garden plot at EG - 2


Nadège



Figure A.5.7. Photo from interview process of urban garden plot at AC



Figure A.5.8. Rainwater collection tank in garden



Figure A.5.9. Biological pest control in AC garden

COLLEGE DOCTORAL PAYS DE LA LOIRE
ED MATIERE, MOLECULES, MATERIAUX & GEOSCIENCES

Université Gustave Eiffel

Titre : Renforcement de la capacité de résilience urbaine à travers les jardins alimentaires urbains multifonctionnels : approche du nexus Alimentation-Eau-Sol

Mots clés : jardins urbains, services et disservices écosystémiques, nexus Alimentation-Eau-Sol

Résumé : Les jardins alimentaires urbains (UFG) sont de plus en plus reconnus comme des Solutions fondées sur la Nature essentielles pour renforcer la résilience et la durabilité urbaines. Cependant, leur viabilité à long terme est mise au défi par un manque d'outils d'évaluation capables de saisir de manière holistique leurs dynamiques socio-écologiques complexes. Les paradigmes dominants, tels que le nexus Eau-Énergie-Alimentation, se révèlent souvent inadaptés à ces systèmes à faible consommation d'énergie et basés sur le sol, car ils tendent à marginaliser le rôle fondamental du sol, le traitant comme un substrat statique plutôt que comme un capital dynamique. Cette thèse comble cette lacune critique en formulant, développant et validant un nouveau cadre conceptuel, le nexus Alimentation-Eau-Sol, un changement de paradigme qui positionne le sol comme l'élément médiateur central dans les paysages comestibles urbain. La recherche emploie une approche mixte et multi-étapes, débutant par une revue systématique qui critique les méthodes d'évaluation existantes et établit la nécessité théorique d'un paradigme centré sur le sol. Ce cadre est testé empiriquement à travers une étude de cas approfondie de 54 jardins collectifs à Nantes Nord, en France. L'application de l'indice génère un profil de durabilité quantitatif et multidimensionnel des jardins, révélant les forces, faiblesses et compromis critiques entre les dimensions de l'alimentation, de l'eau et du sol. En fin de compte, cette thèse apporte à la fois un nouveau cadre théorique et un outil pratique validé pour l'évaluation intégrée des UFGs.

Title : Enhancing urban resilience capacity through multifunctional urban food gardens: Food-Water-Soil nexus approach .

Keywords : urban gardens, ecosystem services and disservices, Food-Water-Soil nexus

Abstract : Urban Food Gardens (UFGs) are increasingly recognized as vital Nature-Based Solutions for enhancing urban resilience and sustainability. However, their long-term viability is challenged by a lack of assessment tools that can holistically capture their complex socio-ecological dynamics. Dominant paradigms, such as the Water-Energy-Food nexus, often prove inadequate for these low-energy, soil-based systems, as they tend to marginalize the foundational role of soil, treating it as a static substrate rather than a dynamic capital asset. This dissertation addresses this critical gap by formulating, developing, and validating a novel Food-Water-Soil (FWS) nexus framework, a paradigm shift that positions soil as the central mediating component in urban edible landscape. The research employs a multi-stage, mixed-methods approach, beginning with a systematic review that critiques existing assessment methods and establishes the theoretical necessity of a soil-centric paradigm. This framework is empirically tested through an in-depth case study of 54 community gardens in Nantes Nord, France. The application of the index generates a quantitative, multi-dimensional sustainability profile of the gardens, revealing critical strengths, weaknesses, and trade-offs between the food, water, and soil dimensions. Ultimately, this thesis contributes both a new theoretical framework and a validated, practical tool for the integrated assessment of UFGs.