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Co-designing grounded visualisations of the Food-Water-Energy nexus to enable urban sustainability transformations

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ABSTRACT

In the past few years, the Food-Water-Energy (FWE) Nexus has emerged as a key concept to address the complex relationships and interdependencies between food, water, and energy systems. Cities are an important context for understanding the FWE nexus given their significant footprints and complex socio-ecological systems, but researchers have only recently started to explore an explicit urban perspective on food, water, and energy interrelationships. This paper tackles a particularly significant knowledge gap in this context by introducing an approach to co-design visualisations of the FWE nexus that are understandable and actionable for the various stakeholders involved in urban governance such as citizens, communities, governments, non-governmental and private-sector organisations. Drawing on user-centred design and inspired by the dialogic pedagogy of Paulo Freire, we present and evaluate the co-design process of a FWE nexus visualisation tool for stakeholders engaged with pre-school education in Słupsk, Poland. Our results provide evidence that this co-design process has been effective to developing a new critical consciousness in the participants about how their everyday choices are related to the FWE nexus, enabling them to change perspectives, leading to more sustainable choices. We propose that our co-design process can be used to develop 'grounded visualisations' of the FWE nexus, i.e., visualisations that are grounded in the experiential situations and lived realities of stakeholders, thus offering an effective support for decision-making that could open pathways to sustainability transformations.

1. Introduction

The Food-Water-Energy (FWE) nexus emerged in the past few years as a conceptual instrument to tackle major challenges concerning the interlinkages between FWE systems. First discussions about the FWE nexus as a mechanism to promote sustainable use of resources were reported at the World Economic Forum in 2008 (WEF, 2011). Afterwards, scientific works have explored various perspectives on the FWE nexus, including security (Bizikova et al., 2013; Bogardi et al., 2012), livelihoods (Biggs et al., 2015), governance (Hagemann and Kirschke, 2017; Weitz et al., 2017) and urban systems (Ramaswami et al., 2017; Romero-Lankao et al., 2017).

Despite the importance of cities in relation to FWE nexus impacts, an explicitly urban perspective on the FWE nexus has only recently started to be explored (Ramaswami et al., 2017). As argued by Mari R. Tye et al. (2022), there are important knowledge gaps to make the FWE linkages understandable to the various stakeholders involved in urban governance (i.e., government, science, business, and citizens), and facilitating cooperation and knowledge exchange among them. A particularly significant knowledge gap lies in how to make the abstract concept of the FWE nexus understandable and actionable for citizens and communities (Tye et al., 2022). This gap is also reflected in the visual representations of the FWE nexus found in the extant literature, either in the form of images or data visualisations. Previous studies have assesed the impacts of different types of images towards increasing awareness and orienting action (Leiserowitz, 2006; O'Neill et al., 2013; O'Neill and Smith, 2014),

Abbreviations: CI, Creating Interfaces, the alias of the research project originating this paper, *"Building capacity for integrated governance at the Food-Water-Energy-nexus in cities on the water"*; FWE, Food-Water-Energy; MVP, Minimum Viable Product; ULL, Urban Living Lab; SDL, Sustainable Development Laboratory.

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as well as for the visual communication of climate change (Daron et al., 2015), but the impacts of data visualisations on how the FWE nexus is understood and communicated have not been systematically investigated so far. Visualising data is increasingly an essential method to enable discoveries and increase understanding of several fields, but much less explored question is "how visualisations elicit change as a joint function of data, design, technology, perception, cognition, cultures and socio-technical systems" (McInerny, 2018, p. 141). Consequently, most of the diagrams, charts, and graphs used to visually depict the FWE nexus are abstract and/or at larger scales (Hatfield-Dodds et al., 2015; Liang et al., 2020; Mahlknecht et al., 2020; Ramaswami et al., 2017; Stein et al., 2018; van Vuuren et al., 2019). This makes it difficult for citizens and communities to relate to and comprehend most of the current visual representations of the FWE nexus.

Nevertheless, we argue that the transformative potential of the FWE nexus can only be fully realised when citizens and communities are able to grasp the connections between the interrelationships of the FWE nexus and their lived experiences. This is especially critical given the overwhelming scientific evidence demanding urgent actions to tackle the climate emergency derived from the conditions in which energy, water, and food are produced, consumed and transported (IPCC, 2022). Whilst this diagnostic is widely accepted by citizens, social movements and governments alike, there's no consensus regarding the actions that are needed to change this situation. This lack of a clear roadmap at all levels (from international to individual), combined with evidence of the worsening situation, has resulted in a series of mental and physical distress problems such as ecological grief, climate trauma, solastalgia, or, more broadly and well-known, eco-anxiety (Panu, 2020). A deeper understanding of how elements of the day-to-day lives of citizens and communities are related to the concept of the FWE nexus could be an avenue for empowerment to support transformations towards more sustainable futures.

To explore this potential, this article is aimed at introducing an approach to co-design data visualisations with stakeholders as a decision support tool capable of activating interactions around the FWE Nexus. Our main research question is: *How can the process of co-designing visualisations help connect people to the food-water-energy nexus to change perceptions as a first step towards sustainability transformations?* To tackle this question, we introduce an approach that considers the FWE nexus as a composite of potential and realised interactions that might be more traditionally considered as science-policy, citizen-science and policy-citizen interfaces. In our approach, visualisation design is closely related to connecting literacies (e.g. visual literacy, numeracy, technicity, knowledge cultures and vocabularies) to bridge various stakeholders and supporting new institutional, cultural, social and epistemic connections that increase involvement, connection, and understanding. In developing a set of connected visual media that span the digital arts and decision support tools, our goal is to activate the FWE Nexus as an ecosystem of knowledge and information, but also of experience and relationships.

To pursue this goal, this article presents a novel approach to co-designing FWE nexus visualisations which employs user-centred design and is inspired by the dialogic pedagogy of Paulo Freire (1970)/(2005), following previous proposals of connecting citizen data and pedagogy (Porto de Albuquerque et al., 2023; Porto de Albuquerque and Almeida, 2020). This study has been developed as part of the international transdisciplinary project "Creating Interfaces: *Building capacity for integrated governance at the Food-Water-Energy-nexus in cities on the water*" with a case study around food choices in kindergartens in Słupsk (Poland), which resulted in a decision-support visualisation tool (Cámara-Menoyo et al., 2022). This article introduces and evaluates the co-design process of this FWE nexus visualisation tool, presenting evidence that this process has been effective to develop a new critical consciousness in the participants about their everyday choices related to the FWE nexus, with the interactive visualisation tool being considered an effective support for decision-making that could lead to more sustainable futures.

The remaining sections of this paper are structured as follows. Section 2 presents the background literature for this study, whilst Section 3 discusses the methods we employed. Section 4 presents the results of our case study and the resulting software prototype. Section 5 presents a discussion of these results, and Section 6 casts final conclusions.

2. Background: visualisations and the Food-Energy-Water nexus

Data visualisations play a crucial role as both tools for research (e.g. Fox and Hendler, 2011) and communicating that research (e.g. Harold et al., 2016) within any domain where we need to make sense of data. Due to the primacy of human's visual sense, for most individuals, data visualisations can provide a means to quickly and efficiently recognise patterns and relationships from data (Anscombe, 1973). Design decisions involving the selection of colours, symbols and graph type, for example, may be led by an understanding of perception and cognition (Ware, 2012).

Data visualisations can also utilise narrative to engage a user and communicate a message, such as by using textual (e.g. Borkin et al., 2015) and storytelling elements (e.g. Segel and Heer, 2010) that determine the emphasis, order and contrasts between views such that the visualisation and its subject matter is revealed and contextualised strategically. The narrative may be interlinked with colours, symbols and graph type, just as emphasis, ordering, and contrasts may be informed by perception.

The processes of exploring the data and designing the visualisation may be concurrent, meaning the visualisations play an important role in mediating and provoking the ideas, discussions, and reactions which feedback into their development (e.g. Hinrichs et al., 2019). Importantly, these interactions with knowledge may happen within and between groups of people and are not carried out in isolation.

This brief sketch of considerations for visualisation design provides some insights into the demands of visualising data. Whilst a visualisation can be quickly produced using software defaults, it will not necessarily suit the task. Indeed, not all visualisations can visualise data (McInerny, 2018). We might not necessarily expect a visualisation to support our goals if it was created without consideration of the particularities of data, tasks, users, context of use and worldviews of end-users. A visualisation could be less effective than desired because there are different users who have different kinds of numeracy, graphical literacy, and domain knowledge, let alone different cultures and ways of knowing and representing the world. Likewise, the design may be more suitable for a different kind of task, or kind of pattern in the data (McInerny, 2018). For these reasons, user-centred approaches are often adopted to understand and negotiate the potentially competing demands on visualisation design (McInerny et al., 2014).

2.1. User-centred design

As is typically the case in human-centred design and user experience (UX), decision-making is informed by research on how the tool (in this case a visualisation) will be used, by whom, and where/when it will be used. It is an increasingly popular way to approach the design and development of visualisations and digital interfaces in a wide range of areas, including research domains such as bioinformatics (e.g. Pavelin et al., 2012) and climate research (e.g. Christel et al., 2018). The design approaches vary widely, in part to alternative forms of expertise, disciplinary approaches (e.g. Sedlmair et al., 2012), as well as very immediate factors such as time, money and other resources. Users/stakeholders can have various levels of involvement, from more distant relationships all the way to becoming part of the research team in a deep co-design process. The nature of the research and design processes are also influenced by how close and fluent the designers and developers are with the domain area, and how experienced they are in the relevant design and development challenges, i.e. by the different "literacies" of stakeholders as regards to the nexus concepts as well as their visual representations. As stated by Fabiola C.Rodriguez Estrada and Lloyd S. Davis (2015), despite the potential of user-centred design for communicating and bridging literacies, the challenge remaining is to find ways to support an interdisciplinary approach to marry design principles and theories —in our case related to the Food-Water-Energy nexus.

2.2. Visualisations of the FWE nexus

Publications in the FWE nexus have been rapidly growing since 2014. Within the figures found in these publications, the nexus has been variously depicted as flows (Bijl et al., 2018; Laspidou et al., 2020; van Vuuren et al., 2019), conceptual relationships (Ramaswami et al., 2017; Stein et al., 2018) or temporal relationships (Hatfield-Dodds et al., 2015; van Vuuren et al., 2019). Some of these differences could be explained by the way in which this complex concept is conceived by different disciplines and perspectives. More practically, a single depiction might be unexpected given that each nexus dimension -FWE- could be represented in data in diverse ways, and are entirely unique entities involved with different systems. The depiction would then depend on three aspects: what data variables are available and similarities between them (e.g. with and/or without spatial or temporal variables, or origin-destination data); whether the data are directly related (e.g. measurements at the same time or place, for the same objects); and how we make links between them conceptually. Thus, whilst we often refer to *the nexus*, any visualisation will have multiple practical constraints and contingencies, and the result will be *a nexus*, in that the visualisation will be a constructed and partial realisation of an abstract concept.

Based on our reading of the FWE nexus literature, we developed four initial principles for visualisation design, described as follows:

Firstly, FWE nexus visualisations have frequently been limited to communication tasks rather than being developed as a research tool that may be an interactive interface. Nexus visualisations that are developed for participatory research should consider how understanding is constructed through reading and interaction (e.g. see reader-driven narratives in Segel and Heer, 2010).

Second, the links between selection of graphics and their suitability are not always clear or reported. Without these kinds of explanations and documentation, then, the rationale and basis for a particular visualisation is not necessarily obvious or contestable (e.g. Dörk et al., 2013).

Third, there is no single representation of the FWE nexus, in part because there are multiple ways in which food, water, and energy are interconnected conceptually and within data sets. A nexus visualisation may be assembled from many forms of expertise and data sources that may or may not have been co-developed or be fully compatible.

Fourth, as an intangible, abstract concept, the nexus has the potential to be overwhelming and bemusing for lay people and non-specialists unless it is defined in their terms. Many nexus issues and research projects are predicated on diverse stakeholder groups developing a shared, actionable understanding (also see science-policy interfaces; e.g. McInerny et al., 2014).

In summary, these principles underlie an important, as-yet under realised potential of FWE nexus visualisations, which we seek to build upon in our approach presented in the following sections.

3. Methodology

This study has been undertaken as part of the “Creating Interfaces” (CI) transdisciplinary project, aimed at addressing capacity building for the urban FWE nexus to make the FWE-linkages understandable to various stakeholders (e.g., city government, science, business, and citizens). To achieve that goal, the project developed and tested approaches for local knowledge co-creation and in three mid-size cities from Poland, Romania, and the United States of America.

All three study cases approached the FWE Nexus by grounding it in local communities through an Urban Living Lab (ULL) setting. ULLs are, places, communities and approaches to foster open innovation with multiple stakeholders and representatives of civil society, through the co-creation, rapid prototyping & testing and scaling-up innovations and projects (Steen and van Bueren, 2017; Suchomska et al., 2024). Because communities and needs are unique and context-specific, the prototypes resulting from the participatory approach in every country differed significantly. In the case of Wilmington (USA), the focus was on food waste, and the visualisation consisted of a scrollytelling, whereas in Tulcea (Romania), the focus was on local food producers and the tool consisted of a Map. The resulting visualisations can also be found in the GitHub repository (Cámara-Menoyo et al., 2022), but due to practical restrictions, it was not possible to implement a full process in all cases. In this paper, we thus focus on one of the case studies: food choices in kindergartens in Słupsk (Poland).

In previous stages of the project, local partners from the Sustainable Development Laboratory (SDL) worked conjointly with headmasters, parents, and children from several kindergartens to understand their concerns and priorities related to sustainable food procurement. This preliminary stage revealed significant difficulties for the stakeholders to understand and relate to the concept of the FWE nexus due to not being deemed relevant for their day-to-day lives. In contrast, these initial engagements clearly identified that the quality of food provided to children was a priority matter of concern not only for parents, but also for kindergarten management and local governmental stakeholders.

To address this gap between the priorities of local stakeholders and an abstract conceptualisation of the FWE nexus, we developed an innovative process to engage end-users and researchers from multiple disciplines in the co-design of FWE visualisations. Our aim is not just to design a digital artefact per se, but to implement a learning process to co-produce knowledge through the co-creation of a visualisation artefact. We thus adopt a normative approach to co-production following a “social learning” lens (Bremer and Meisch, 2017) in line with recent scholarship emphasising the importance of participatory and transdisciplinary approaches to connect science and society (e.g., Norström et al., 2020; Ruiz-Mallén et al., 2016; Turnhout et al., 2020). However, despite widespread interest in co-production to enable transformations towards more sustainable socio-ecological relationships, there still is insufficient understanding of the collaborative processes that may enable transformative change (Chambers et al., 2022). To fill this gap, we draw on recent works that adopted principles from the dialogic pedagogy developed by Paulo Freire (1970)/(2005) for transdisciplinary co-production towards sustainability transformations (Porto de Albuquerque et al., 2023; Vilsmaier et al., 2020). In contrast with these previous studies, our co-design process is aimed at specifically investigating the potential of co-designing visualisations of the Food Water Energy nexus to open up pathways to sustainability transformations.

Drawing on Freire, João Porto de Albuquerque and André Albino de Almeida (2020) have proposed to see the engagement of citizens in scientific activities of data generation from a pedagogical lens, identifying a “constitutive tension” between the perspective of scientists and citizens. In our case, we have observed this tension reflected into the asymmetric understandings around FWE of citizens and scientific conceptualisations of the FWE nexus. To address this, Freire’s methodological approach proposes that any pedagogical process should start with concrete, existential situations of people as the basis for a dialogue that bridges those perspectives. Through the dialogue and connections between different perspectives, citizens can acquire a new “critical consciousness” about their lived situations and experiences, which will open up novel pathways for transformation of the current circumstances (Porto de Albuquerque et al., 2023). Bringing this approach to our context, we reconceptualise the process of designing FWE nexus visualisations as an opportunity for transformative learning (Mezirow, 1978). The acquisition of this critical consciousness about their realities and how they are connected to the interrelationships between food, water and energy, enables stakeholders to transform problematic frames of reference to make them more inclusive, open, reflective, and thus, more suited to guide action (Mezirow, 2018, p. 92). This new understanding of the relationship between day-to-day choices and experiences of citizens and their socio-ecological implications for the FWE nexus is what we call a "grounded FWE nexus". This is, a critical perspective about the interconnections between food, water, and energy which is grounded in the participants' concrete existential situations and able to unlock pathways to sustainability transformations.

The next sections describe an overview of our co-design process, followed by a description of each of the methodological steps undertaken.

3.1. Process overview

The co-design process to produce a tool to visualise the grounded FWE nexus was implemented between 26th June 2020 and 30th September 2021, involving the visualisation team (UK), local partners (PL) and stakeholders (the end users), see Table 1. The process followed a User-Centred Design for Science Communication approach (Rodríguez Estrada and Davis, 2015), inspired by agile development (Beck et al., 2001; Shore and Chromatic, 2007). It consisted of 4 different stages (see Fig. 1): 1) Foundations; 2) Software Development; 3) Transdisciplinary Team Review; and 4) Evaluation. Each of them was implemented through a series of activities summarised in Table 1, following bi-weekly meetings between the local partners working in Poland and the visualisation team working in the UK.

3.2. Stage 1: Foundations

This first stage starts from an existing relationship between the local partners and members of kindergarten communities (who would become the stakeholders and end-users). In previous conversations, it was clear that stakeholders were interested in sustainable food procurement in their menus, but were unaware about how it was related to the FWE nexus, which was the theme of the entire CI project.

This first stage was aimed at defining a common ground and setting the foundations of the relationship and the process through two workshops: the first one was aimed at establishing a common language by discussing various possible visualisation types and their fit for different purposes, i.e., to identify the existing "visualisation literacies". The second one, was aimed at "grounding" the discussion by identifying the end users' aims.

Table 2 shows the three end-users types and their aims, as well as how the narrative evolved from a generic initial goal to a more specific one by subtle, yet crucial, changes in the subject of analysis.

3.3. Stage 2: Iterative software development

This iterative stage was implemented through a series of weekly workshops (*"sprints"* in agile terminology) that led to a concept for the "Minimum Viable Product" (MVP), i.e., a viable software prototype of the visualisation tool. Each of these sprints were structured in three parts: 1) complete a series of thematic tasks; 2) identifying next actions for the following week; and 3) assess the results from the previous one. More specifically, the tasks for each of the sprints were:

1. Define the needs for each user group.
2. Translate those needs into a series of specific questions that those users would like to know an answer to.
3. Identify the required data to give an appropriate answer to each question.
4. Identify the right visualisation to present the answers to each question.
5. Prioritise the visualisations according to their importance (for the project and stakeholders) and their feasibility (complexity, data availability).

Due to language barriers between the researchers implementing the data visualisation tool and the stakeholders, this stage was split into two parallel streams: one with researchers and local partners and another one with stakeholders and local partners. Local partners, therefore, acted as mediators and proxies of the end-users and the visualisation team, respectively, feeding the others based on the prior meetings.

Fig. 2 displays these tasks and the results of the process. The MVP was reached after repeating steps 3–5 per every user group until the development time was exhausted, and everyone was happy with the results.

3.4. Stage 3: Transdisciplinary team review

The MPV was tested with the broader CI consortium during an internal workshop. Partners were divided into groups and had to interact with the tool to answer a different research question regarding the FWE nexus and fill a feedback questionnaire. This stage also served as a pilot for the evaluation workshop with end users.

3.5. 3.5 Stage 4: Evaluation with end-users

After addressing issues raised after the previous stage, a working prototype was achieved. The FWE visualisation tool prototype was tested by a group of 17 stakeholders: 2 directors of public kindergartens, 3 City Hall representatives, and 12 parents. The workshops allowed us to evaluate the tool in terms of usefulness and validity of collected data, technical solutions and possible scaling up. The workshop was based on group work, which consisted in the participants completing prepared tasks aimed at familiarising them with the visualisation tool. Additionally, each of those tasks was followed by a debriefing group discussion (see Table 3) aimed at reflecting and discussing the findings about the usefulness of the visualisation of our prototype, the FWE nexus, and the impacts on their decisions. Finally, each participant filled in a short survey with a combination of closed answers and free text questions aimed to assess the effectiveness of our prototype tool to support people in accomplishing the tasks proposed, as well identifying lessons learnt.

Participant's feedback was captured by the local partners via participatory observations, a questionnaire and through notes taken after informal conversations. This was later shared with the researchers, and was analysed using content analysis and descriptive statistics. No personal data about the participants was collected, and informed consent was obtained from participants through consent forms, following the ethical approval guidelines of Nicolaus Copernicus University.

4. Results: implementation of the visualisation tool

This section summarises the results achieved by our co-design process from two complementary standpoints: those related to the visualisation tool (Section 4.1) and those related to the outcomes of the evaluation workshop (Section 4.2).

4.1. The prototype: A visualisation tool for Słupsk's kindergartens

The prototype of a tool capable of visualising a "grounded FWE nexus" while engaging a defined target audience was shaped in the form

Table 1
Summary of activities in each stage of the co-design process.

Stage	Timeframe	Activities	Participants
I. Foundations	May 2020	2 online workshops	Visualisation team, local partners and end users
II. Iterative Software Development	26th May - 21st July 2021	5 development sprints, consisting of biweekly (online) meetings	Visualisation team and local partners
		5 biweekly (online) meetings to prepare and respond to upcoming/previous development sprints	Local partners and end users
III. Transdisciplinary Team Review	11th Oct 2021	Workshop, piloting the visualisation tool (online)	Representatives of all CI consortium
	19th Oct 2021	Presentation in Workshop: Governance & Capacity building - Urban 'Food-Energy-Water Nexus'	Researchers, and extended stakeholders (end users and representatives of municipalities, private sector and general public)
	15th Sept 2021	Symposium on the Food-Water-Energy Nexus	Researchers, practitioners, General public, Postgraduate students, Other audiences
IV. Evaluation	8th Nov 2021	Workshop (face to face)	Local partners and end users

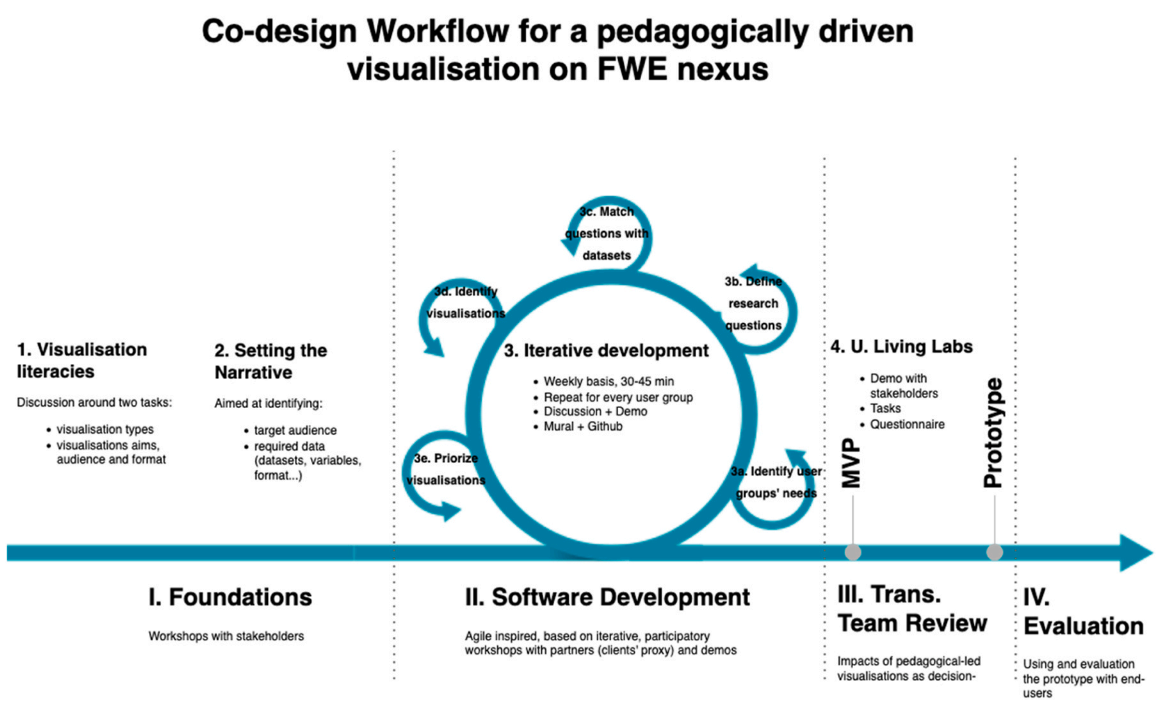

Fig. 1. Diagram of the steps of our co-design process of grounded FWE visualisations.

Table 2
Three main user groups identified and their goals.

End-users types and aims	Evolution of the visualisation tool's goals
• **Parents:** monitor what their children eat (health concern). • **Schoolmasters:** want to demonstrate that their food choices are in line with regulations and parents' expectations. • **Policymakers:** want to know if the food served in their kindergartens is good enough. Have an interest in promoting local consumption and environmentally wise policies.	1. Interest in sustainable food provision 2. Assess **healthy food** in kindergartens. 3. Identify **food that is good** for children (health) and the environment (footprint). 4. Understand the implications of **food choices** in kindergartens for the health and the environment.

of an interactive web dashboard[1] (Cámara-Menoyo et al., 2022). The dashboard, which can be publicly accessed,[2] visualises data collected in previous stages of the project about the meal menus from three kindergartens from Słupsk and the corresponding ratings provided by parents and children. These citizen-generated data are combined with other available datasets related to FWE (Greenhouse Gas Protocol, 2021; Mekonnen and Hoekstra, 2011, 2012). Therefore, the aim of this visualisation tool is to enable a more comprehensive understanding of the implications of day-to-day decisions about food provision and consumption regarding their relationships to wider FWE systems. The core idea is to investigate how meals in kindergarten menus can be turned into drivers for positive change for the health and the environment.

As depicted in Fig. 4, the dashboard interface is organised in four main sections: Overview, Food, Energy, and Water (plus an extra

[1] Technically, the tool consists of a script written in R programming language, which produces a standalone web file (HTML) that can be hosted on a server and accessed with any web browser. Both, code and an instance of the dashboard, can be accessed in the GitHub repository: https://github.com/IGSD-UoW/wfenexus

[2] An English translation can be accessed here: https://igsd-uow.github.io/wfenexus_demo/slupsk/slupsk_dashboard_en.html

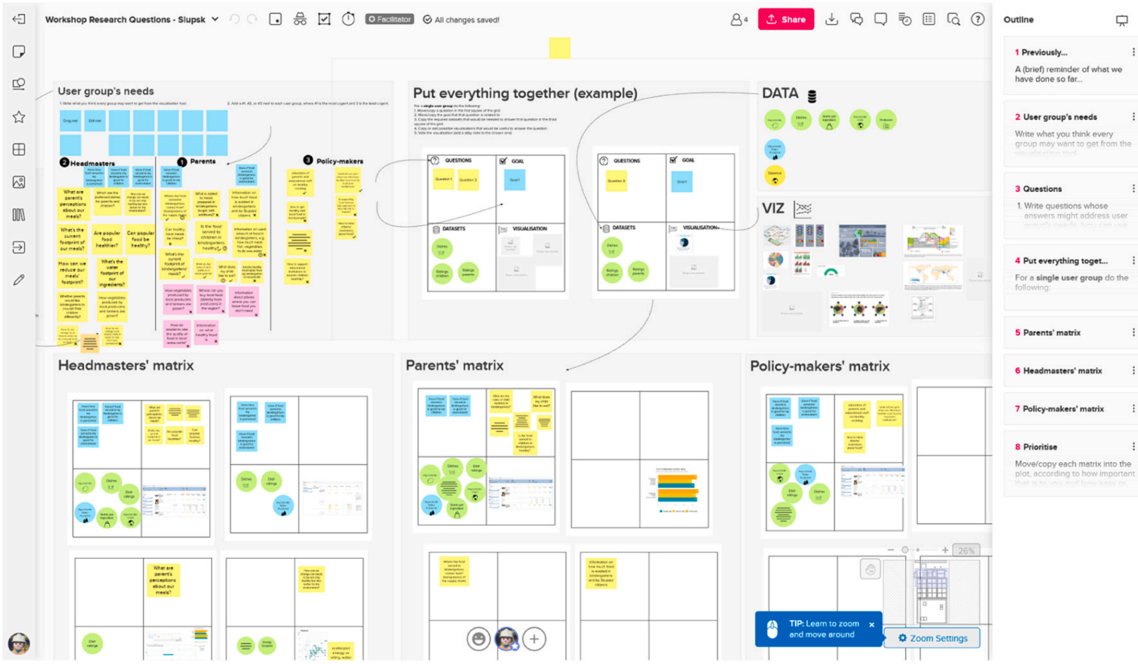

Fig. 2. Canvas used for conducting the sprints. Each grid represents a matrix for every user group that was to be filled with their needs, questions, and possible datasets and visualisations needed to answer them.

Table 3
Tasks performed by end-users and discussion questions.

Task	Discussion questions
Identify highly rated meals and the lower rated meals	Does that match your expectations? What do you think was the criteria used by parents to give higher and lower ratings? And for children? Do you think those meals are good for children? Do you think those meals are good for the environment?
Identify meals with higher footprint	Do you identify any patterns in the meals with a higher footprint?
Identify ingredients with higher footprint	What kind of ingredients have a greater footprint? What strategies could be followed to reduce meals' footprint?
Share with the group any figure/data you found more interesting, or you didn't know	What have you learnt today?

"About" section with definitions and considerations in relation to the data, units, and measurements used). Each section provides several visualisations with information about the meals, their composition, energy footprint, water footprint and ratings, where suitable. Based on the first stages of our co-design process, we decided to use a small set of familiar visualisation types instead of using more specialised and complex visuals. Table 4 below summarises the types of visualisations that were used and their purpose.

The decision of presenting the tool as an interactive dashboard instead of using other formats (such as reports, infographics, or slides) was taken to deliberately avoid a linear, pre-defined narrative that could inform building scenarios (Kok et al., 2007; Swart et al., 2004) to be implemented and evaluated in future stages. Thus, the tool allows users to freely explore the connections to FWE nexus elements depicted in the visuals and helps them build their own narrative based on their interests and personal circumstances.

As an example, a possible narrative could result from the following sequences of actions:

1. Identification of meals that have a large water and energy footprint and identification of patterns in their ingredients, e.g., local vs non-local production; animal vs plant-based ingredients (Fig. 3);
2. Comparing the water footprint of various ingredients, based on their origin, i.e., worldwide average vs produced in Słupsk (Fig. 4)
3. Comparing the water footprint of ingredients, focusing on their origin type, i.e., animal vs plant-based (Fig. 5);
4. Comparing the energy footprint of ingredients, focusing on their origin type, i.e., animal vs plant-based (Fig. 6);
5. Discussing decisions to be made when identifying apparently contradictory results (e.g., what may look good in terms of energy may not be good in terms of water). This could trigger generating further visualisations -such as Fig. 7- or identifying the need for new data.

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4.2. Outcomes of the evaluation workshop

This section refers to the final stage of our co-design process, which consisted of an evaluation workshop. After using the tool to conclude the tasks we proposed around the connections to the FWE nexus, the general evaluation of the session was very positive: according to the questionnaire's responses, all the 16 participants stated that they found the workshop (and the way it was conducted) very interesting. Even the most critical participant acknowledged that it provided "a new way to learn about meals and products". The most significant outcome of the workshop was that almost everybody (4 people strongly agreed, 9 agreed and 3 were unsure) reported having learnt something new about the FWE nexus, thanks to the data visualisation tool. What is more, most of them (4 strongly agreed and 9 agreed, vs 3 who were unsure) claimed to have acquired a more profound understanding of the interconnections and impacts between food, water, and energy through the interaction with our visualisation tool. This is particularly relevant given the lack of prior interest in the FWE nexus: 13 out of 16 participants declared their motivation to attend the workshop was not related to the FWE nexus. Fig. 8

During the workshops, participants pointed to the innovative nature of the food knowledge provided by the visualisation tool. Participants

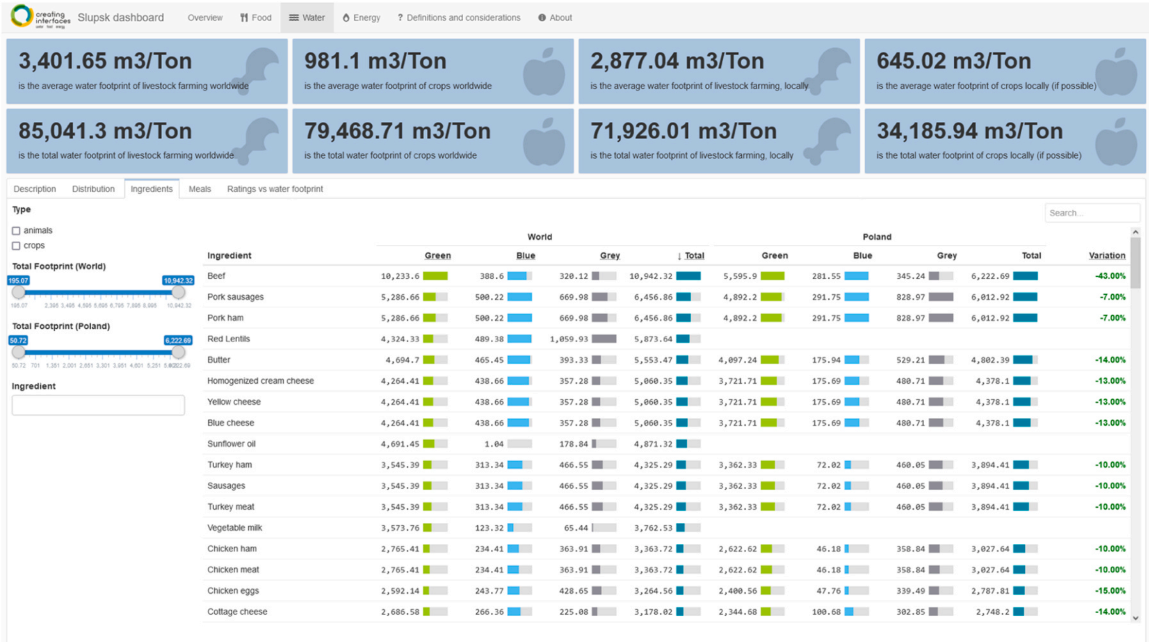

Fig. 4. Comparison of ingredient's water footprint based on their origin. Figure on the right displays the difference between the world's average total water footprint and total footprint if the same ingredients were produced locally (Negative values imply water footprint reduction).

Table 4
Visualisation types used in the dashboard alongside purpose and examples.

Visualisation type	Purpose	Examples	Interaction
Table	Data exploration	Meals composition, ratings and total footprint. Ingredients' footprint breakdown	Filters, sorting, tooltips, nested tables
Barplot	Amounts and rankings	Most used Favourite meals by kindergarten	Tooltips
Treemaps	Hierarchical proportions	Ingredients' origin	Tooltips, breadcrumbs navigation
Scatterplot	Correlations	Parents' ratings and childrens' ratings, Ratings and footprint, ingredient's usage (weight) vs footprint	Tooltips, filters

indicated that the visualisation of water footprint (6), CO_2 emissions and energy use (7) associated with meal recipes was particularly appealing and novel for them. Some participants indicated their surprise with the data visualised, for example, with the amount of CO_2 emissions related to specific products. Some participants (7 strongly agreed, 4 agreed) also stated that if it were not for their contact with the tool, they would not have been interested in this topic by themselves. This is a particularly significant result because at the beginning of the co-design process, participants had a narrower, primary interest in the quality and safety of the food provided to children in kindergartens. As such, we observed that the interaction with the tool has triggered a change of perceptions in citizens, who moved from a more individualistic interest in food consumption to a broader view about the environmental implications of food production and consumption.

A result of this broadened perception was the suggestion of additional datasets to be included in future versions of the visualisation tool. For instance, one participant suggested that knowing their food waste (i.e., the amount of food leftovers after meals) was important, and therefore data needed to be added. This is a significant indicator, which is present in the public debates and in the consumer culture; its addition to the tool could be useful to raise awareness about the link between food and environmental costs.

When asked about the most interesting findings after having interacted with the visualisation tool at the end of the session, there were two groups of concluding remarks: one concerned with the implications of food choices for the children, and another one concerned with the environmental implications. In the first group, they emphasised the subjective dimension of food preferences (that include perceived health but also taste or satisfaction), which can significantly differ among individuals, and specifically from adults to children. In that case, they valued the information provided regarding calories, allergens, ingredients, or meals' pictures to support them making better choices. Users appreciated the role of the meal pictures, which can allow them to talk about food more easily with children at home and in kindergartens. In face of otherwise limited opportunities to engage citizens in a discussion about the environmental costs associated with public food catering, mainly due to a lack of knowledge and awareness, the workshop has provided evidence that the visualisation tool has the potential to make the FWE nexus more interesting and relevant in connection to a matter of concern to people as regards to kindergartens.

This fact was even more clear in the second group. One participant specifically admitted not being aware of the environmental costs of food production in their daily lives, and there was consensus that knowing the CO_2 emissions and water consumption of meals would be crucial to improve their choices. Both groups identified knowing the origin of the ingredients as key information needed to make informed decisions on food choices, due to their significant impacts on health and environmental footprint.

Workshop participants pointed to several concrete possibilities for the practical use of the data presented by the tool (Table 5). Not only in kindergartens and other educational institutions, but also in citizens' everyday food consumption practices, the data can be used to select specific products, source them and decide which meals will be cooked, as well as to discuss the impacts of food consumption and production on the environment. There was also a suggestion about the possibility of decision-making at the level of not just one kindergarten, but the whole system of public educational establishments in the direction of large-

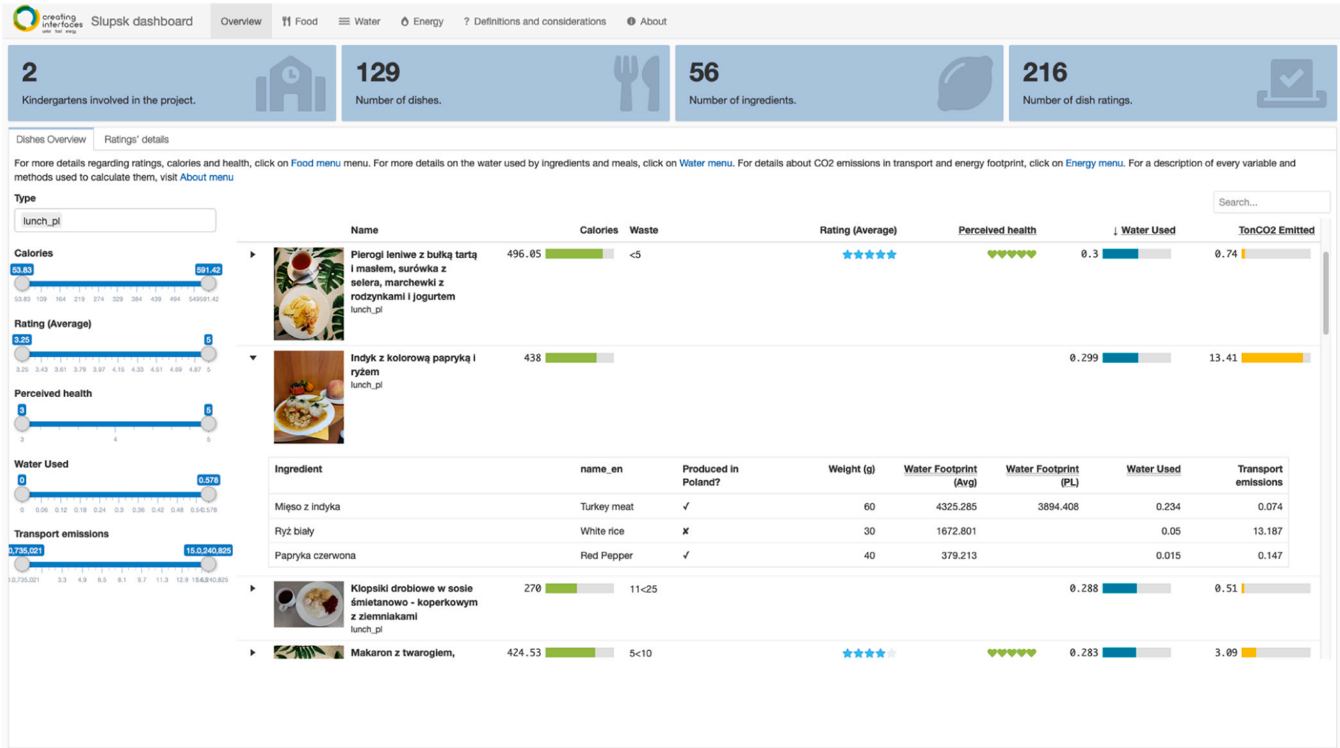

Fig. 3. List of lunch meals, displaying meal's overview and ingredients' details (i.e. origin). The list has been filtered to display lunch meals only, and sorted by water used.

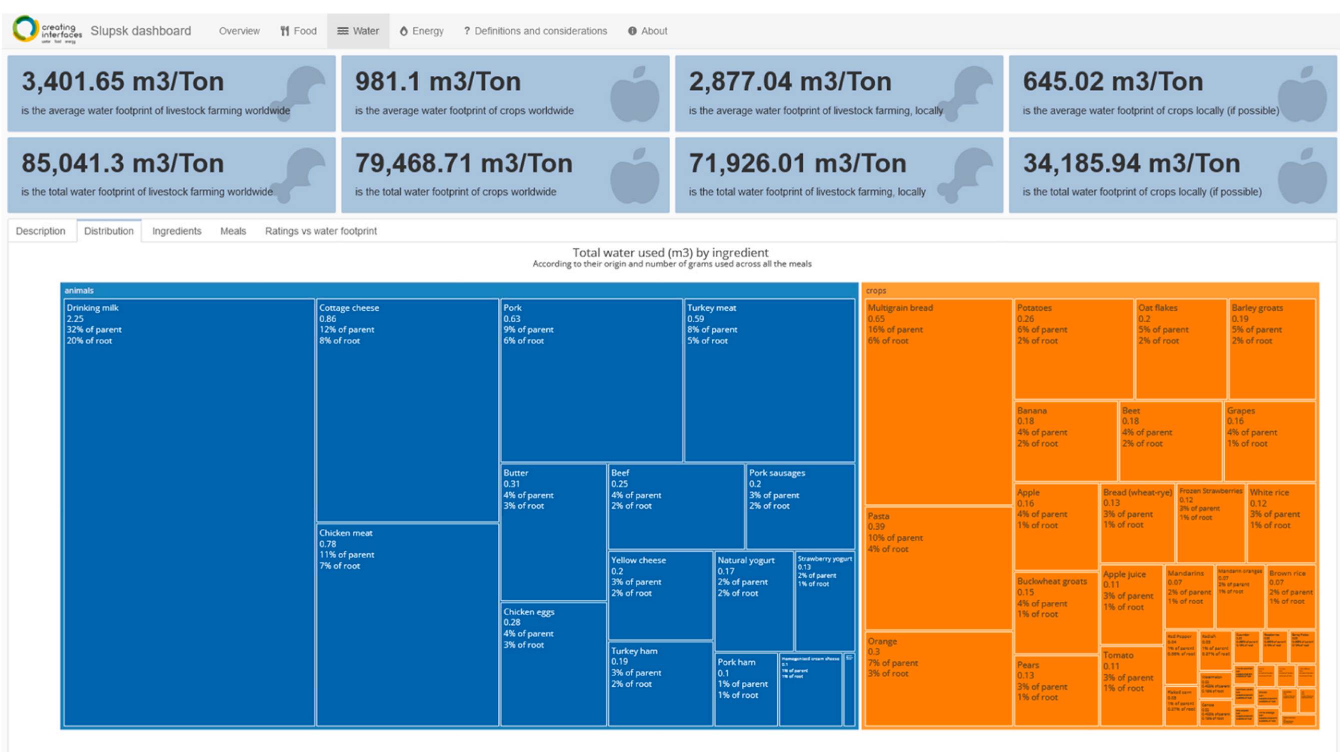

Fig. 5. Treemap displaying ingredients' water consumption and how they compare in relation to the total. Size represents water used by ingredient, colour ingredient's origin (animal -blue- vs plant-based -orange).

scale procurement from local producers. This is a significant result of our study, which indicates a real possibility of starting a broader discussion about the environmental costs of public food catering in kindergartens in Słupsk. When asked about who should be responsible for providing all that information that they identified as relevant for their choices, the vast majority pointed to the institutions that actually decide on the

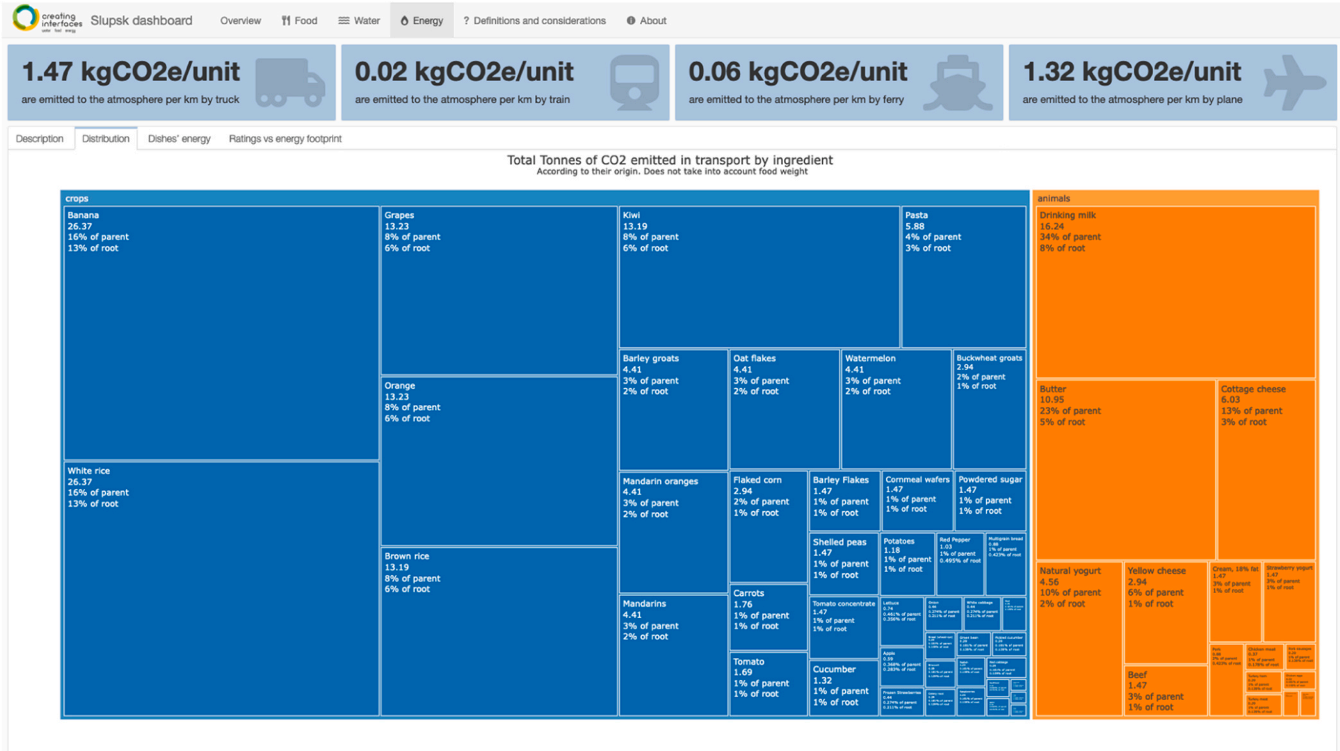

Fig. 6. Treemap displaying ingredients' energy consumption and how they compare in relation to the total. Size represents CO2 emitted in transport by ingredient, colour ingredient's origin (animal -orange- vs plant-based -blue).

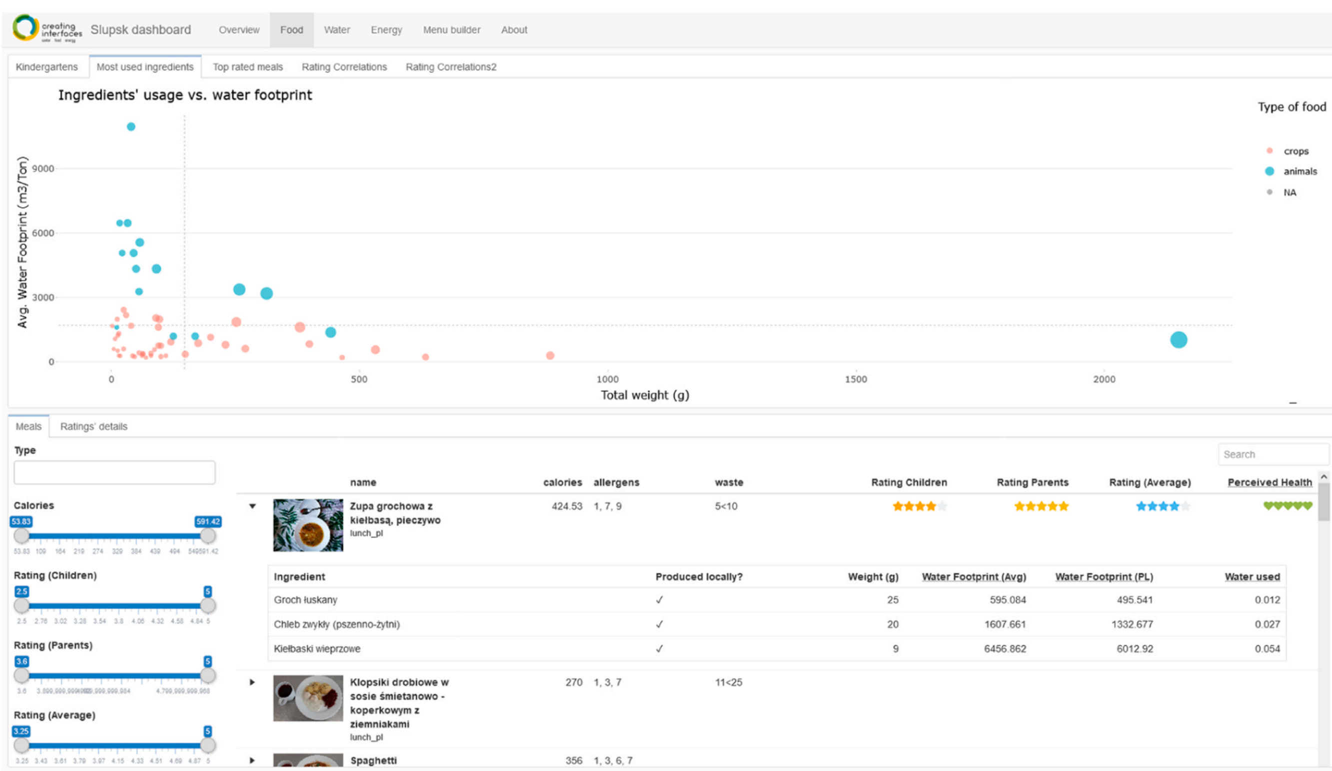

Fig. 7. Scatter plot comparing average water footprint (y-axis), usage (total weight, x-axis) and total consumption (size) by ingredient and ingredient type (colour).

menus (i.e. kindergartens, schools, canteens) followed by food producers and manufactures and, to a lesser extent, to institutions and organisations working in environmental issues. This was followed by discussions about the role city council and policymakers could play in favouring sustainable food procurement. Given that some participants were city council representatives, the idea of using this experience as a

Fig. 8. Participants interacting with the tool to solve the assigned task in the evaluation workshop.

Table 5
Evaluation of the usefulness of the visualised data and the IT tool by the participants of the workshop.

Kindergartens	Environmental and Sustainable Food Public Procurement.	Citizens
• Shopping and menu planning • Selection of appropriate nutritional products • Making meals more child-friendly • Organisation of group procurement for kindergartens	• Education on CO_2 emissions, water, and energy consumption and production • Raising citizens' knowledge on environmental issues related to food • Raising citizens' awareness for eco-living	• Inspiring parents to cook different dishes • Foster opportunities for parents to talk to their children about food appeal and healthiness • Suggesting changes to the kindergartens' menus • Fostering opportunities for learning about local producers

pilot for developing policy recommendations at city level was explored.

On an individual level, users pointed to the visualisation tool's importance for expanding citizens' food knowledge and awareness, and the possibility of building local food knowledge from the bottom-up, for example by adding information about local producers in the future.

While participants were overall satisfied with the tool (3 strongly agreed, 8 agreed, 3 were neutral) and labelled it as "intuitive" and "easy to use", there was space for constructive criticism and suggestions for future improvements. Two types of feedback were given: those related to the current status of the tool and suggestions for future improvements. In the first group, two people reported feeling overwhelmed by the amount of information provided by the tool, which was considered to be excessive. Missing Polish translations were also reported to be a problem to perform some of the tasks. When asked about what could be improved in future versions, some people suggested including new types of data (e.g., adding links to information about local producers or about the amount of food waste per meal) or new features, such as the suggestion for an additional section in which parents could share healthy recipes, as well the addition of some conclusions or summary of key takeaway points.

5. Discussion

The overarching research question we explored in this study is how a co-design process of "grounded visualisations" combining agile software development methods with a Freirean dialogic pedagogy could contribute to connecting people to the FWE nexus to change perceptions as a first step towards sustainability transformations. To answer these questions, we conducted a case study and evaluated whether our proposed co-design process and the resulting interactive visualisation tool were able to afford a new critical consciousness, fostering changes in perceptions towards more sustainable choices. Based on our experience, the results are promising.

As demonstrated, this iterative co-design process not only yielded locally meaningful visualisations of FWE datasets, but it also facilitated a dialogic learning process that leveraged the affordances of these visualisations to enhance critical awareness among participants about their daily choices.

Our study documents three scenarios where perception changes toward the FWE Nexus were observed. First, a vast majority of participants reported not having prior knowledge about the FWE Nexus, whilst a majority declared to have acquired increased awareness of the implications of food choices for the environment (energy and water) after the participatory process.

Second, some participants specifically reported having learnt more about specific decisions they can make regarding their food choices to minimise their impact while offering healthy options for their children. These two types of knowledge gained by participants are associated with changes in their perceptions about the FWE nexus, since they acquired a different perception of how different aspects of the food, water and energy systems in their environment are connected among themselves and impacted by their own choices and actions. This is related to their capacity to identify and understand cross-domain relationships and to apply the FWE nexus concept at the local level, which has been suggested by Huntington et al. (2021) as a pathway for long-term sustainability.

Third, the lessons learnt from the process and the interactions with our tool enabled discussions outlining possible actions towards sustainable food procurement choices, from the individual scale to city level. The city council representatives who participated in our study saw an opportunity to scale up the pilot to other institutions, which is indicative of them having changed their perceptions about the importance of considering the FWE Nexus in policy and practice. Furthermore, the combination of these observations suggests that some action following the process is to be expected, as outlined in Table 5, even if it still needs to be empirically verified.

Further follow-up is necessary to assess if the observed perception changes will lead to behavioural changes, and these into longer-term impacts. Unfortunately, plans for follow-up activities, such as focus groups or scenario-building workshops, were thwarted by COVID-19 restrictions, which severely hampered and delayed any activity involving social interaction.

Nevertheless, we contend that our study addressed two major barriers that non-expert participants face when dealing with the FWE nexus:

the inability to understand data and data visualisations (i.e., data literacy), and the inability to feel compelled to action by the abstract concept of "the nexus". These barriers were addressed by adopting a Freirean pedagogical approach that results in "grounding" the FWE nexus visualisations into scenarios, lived experiences, and concepts that are specific, tangible and are part of people's everyday decisions.

As a result, our "grounded FWE visualisations" are significantly different from the mostly abstract, large-scale and conceptual visual representations of the FWE nexus found in previous literature (Hatfield-Dodds et al., 2015; Liang et al., 2020; Mahlknecht et al., 2020; Ramaswami et al., 2017; Stein et al., 2018; van Vuuren et al., 2019). In this way, our study provided evidence that the interactive, grounded FWE visualisations of our tool enable a mutual learning process where citizens and governmental stakeholders can discuss options and pathways to move away from the *status quo* towards more desirable options.

This process is related to, at least, three different roles of data for enabling sustainability transformations (Porto de Albuquerque et al., 2021) in combination with the medium used. First, grounded FWE visualisations can support decision-making by helping stakeholders refer to how to make more sustainable choices in their local context. Second, data visualisations also enact a metalingual function, i.e., they can enable new understandings of the participant's local realities and the interdependencies between their actions and those of other stakeholders. Third, the use of interactive data visualisations favours the creation of multiple narratives to inform building scenarios to assess the FWE nexus in context (Kok et al., 2007; Swart et al., 2004) to be developed in further research (Johnson and Karlberg, 2017). We contend that the combination of these three aspects results in a grounded FWE nexus that connects to lived experiences and problematises frames of references to activate transformation was crucial.

Of course, the new awareness and critical consciousness that can be achieved with "grounded FWE visualisations" are just the first step to opening pathways towards long-term, sustainable and transformative change, and thus must be cultivated by further action (Chambers et al., 2022). In our study case, our transdisciplinary co-design process has supported stakeholders to identify barriers which would need to be addressed to enable such changes: for instance, stakeholders concluded that the city of Słupsk does not currently have a holistic and environmental policy and thus lacks a more systematic approach which could embrace the FWE nexus perspective in their decision-making processes. This makes it challenging to institutionalise the experimental positive results and findings achieved in our ULLs, which echoes some well-known challenges related to the governance of urban sustainability transitions (Bulkeley et al., 2016).

We acknowledge that our study has some important limitations. Challenges related to power dynamics (Turnhout, 2022), such as the potential dominance of researchers' voices, or the participants' agency and experience, are frequent in participatory processes and need to be considered in further research. Furthermore, while it could be argued that those who attended the workshops were already relatively empowered, it is also true that their initial motivations did not show a strong interest around the FWE nexus. Consequently, our process and visualisation tool seem able to contribute positively to the observed perception changes, which will be crucial for effective societal responses to the challenges of climate change. We are aware that the relationship between acquired knowledge and changes in perception and behaviour is not linear, but several studies have found that some particular types of knowledge, such as the causal knowledge visualised in our tool, are positively correlated with perception changes around climate change (Bord et al., 2000; Shi et al., 2015). However, the translation of the changed perceptions into action will be mediated by a myriad of factors, including psychological factors that could be further explored in relation to the literature of environmental psychology.

Therefore, our study also opens important avenues for future research. We believe the following ones are particularly relevant: 1) addressing how transdisciplinary research in general, and grounded FWE visualisations in particular, could be institutionalised to support governance and decision-making related to the FWE nexus in cities. 2) how this prototype and approach can be scaled up or implemented in new, different contexts, and how it could motivate people to transformative actions following on from their changed perspectives.

6. Conclusion

The FWE nexus is a powerful conceptual instrument to promote sustainability transformations by addressing the multiple interlinkages between the various food, water, and energy systems. Due to its complexity, the FWE nexus has been approached from different angles and disciplines, yet it faces challenges in increasing stakeholders' engagement that hamper the full realisation of its transformative potential.

In this methodological paper, we have presented the experience of having piloted and tested an approach to co-design "grounded visualisations" of the FWE nexus and the resulting interactive visualisation tool for a particular use case: food procurement in kindergartens in Słupsk (Poland). Our approach innovates in two key distinctive features: 1) grounding the FWE nexus following a pedagogical approach that connects to lived experiences and problematises frames of references to activate transformation; and 2) the use of data visualisations to critically enquiry and learn about the nexus. The combination of these features results in data visualisations that "ground" FWE nexus by connecting to lived experiences and problematising frames of references to open transformation pathways.

The outcomes demonstrate a shift in perspectives towards the FWE Nexus that resulted from the design process and the interaction with our visualisation tool. Although further investigation is needed of whether these changed perceptions will be followed up by concrete action, we contend, building on Freire's pedagogy, that the acquired critical consciousness is an essential prerequisite for truly transformative action towards positive outcomes.

Therefore, we see it as a first step to opening new data-enabled transformation pathways to sustainability (Porto de Albuquerque et al., 2023), not only through improved individual choices, but also by enabling new collective action, change of policies and organisational procedures, as well as new governance arrangements. Future work should also investigate other scenarios and usages for our "grounded FWE visualisations". Even if our resulting visualisation tool (Cámara-Menoyo et al., 2022) is a tailored solution for the specific context we investigated, it can be used as an inspiration for exploring the FWE nexus in other cities and scenarios. Our proposal is flexible enough to deal with the complexities of the FWE nexus when adapted to different audiences and approaches. New co-design processes following our approach could be conducted to explore its usefulness in other contexts.

The work presented here can be used to inspire future work that empowers citizens, local city governments, and stakeholders to generate action-oriented knowledge about the interrelationships between food, water, and energy. We hope this approach can be extended and adapted to other usages and scenarios, leading to more sustainable futures.

CRediT authorship contribution statement

Carlos Cámara-Menoyo: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **João Porto de Albuquerque:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Conceptualization. **Joanna Suchomska:** Writing – review & editing, Methodology, Formal analysis. **Grant Tregonning:** Methodology. **Greg McInerny:** Writing – review & editing, Methodology, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Joao Porto de Albuquerque reports financial support was provided by United Kingdom Research and Innovation. Economic and Social Science Research Council (ESRC).

Data Availability

The data and software code that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.6566158.

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